(Results and) Prospects of strangeness nuclear physics at J-PARC

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Neutron Star Matter

Contents

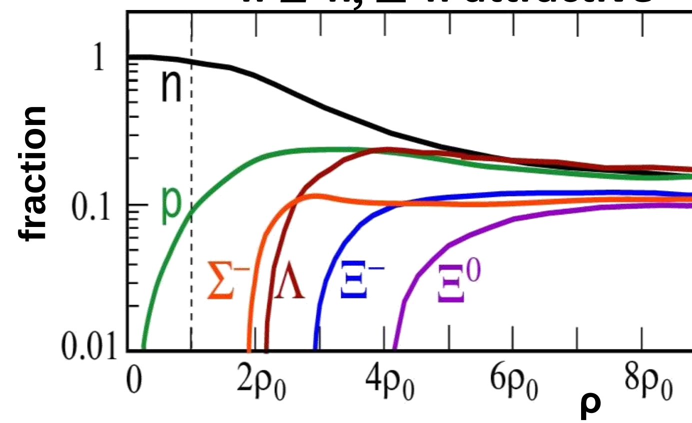
Strangeness Nuclear Physics experiments at J-PARC and neutron star matter

Under preparation

Ready to run

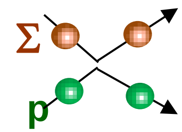
Partly took data

If Σ^-n, Ξ^-n attractive



Ishizuka Ohnishi et al.

- ◆ $\Sigma^{\pm}$p scattering **E40**



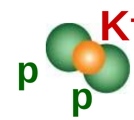
-> Σ^-n (= Σ^+p) , Σ^-p->ΛN interaction

=> Σ^- exists in n-star?

- ◆ γ spectroscopy of Λ hypernuclei **E13**
- ◆ n-rich hypernuclei by (π^-,K^+) **E10**

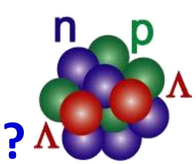
-> ΛN, ΛN-ΣN (ΛNN) interaction => Fraction of Λ in n-rich matter

- ◆ K^-pp by ^{3}He(K^-,n) **E15**
- ◆ K^-pp by d(π^+,K^+) **E27**



-> K^{bar}N interaction in matter => K condensation in n star?

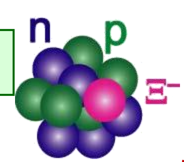
- ◆ $\Lambda\Lambda$ hypernuclei **E07**



=> Λ fraction, $\Lambda\Lambda$-superfluidity

-> $\Lambda\Lambda$ interaction , $\Lambda\Lambda$ correlation?

- ◆ Ξ hypernuclear spectroscopy **E05**



- ◆ Ξ atom X rays **E07** **E03**

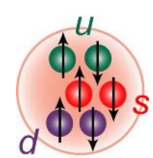
-> ΞN interaction

=> Ξ^- exists in n-star?

- ◆ $\Lambda\Lambda$ correlation and H dibaryon **E42**

-> $\Lambda\Lambda$ interaction in free space

Origin of short-range repulsive core in BB force



=> Λ fraction

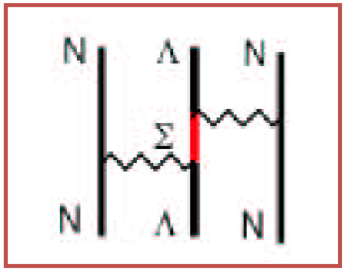
$\Lambda\Lambda$-superfluidity

2. Neutron-rich Λ hypernuclei

Neutron-rich hypernuclei

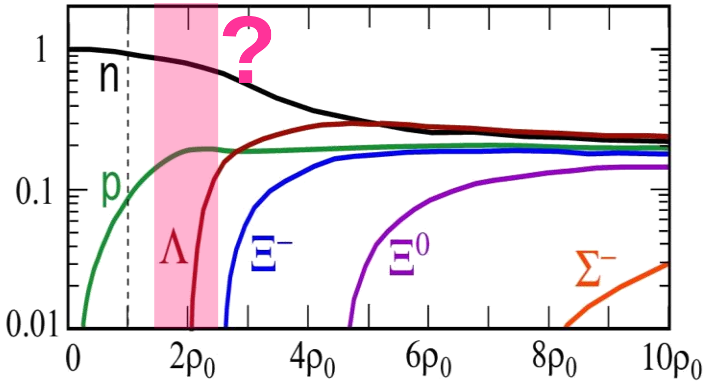
- Strong mixing of ΛN-ΣN B.F. Gibson et al. PRC6 (1972) 741, etc.
- Coherent effect in proton/neutron-rich nuclei

Akaishi et al. PRL 84 (2000) 3539



Larger mixing in a host nucleus with larger I_A

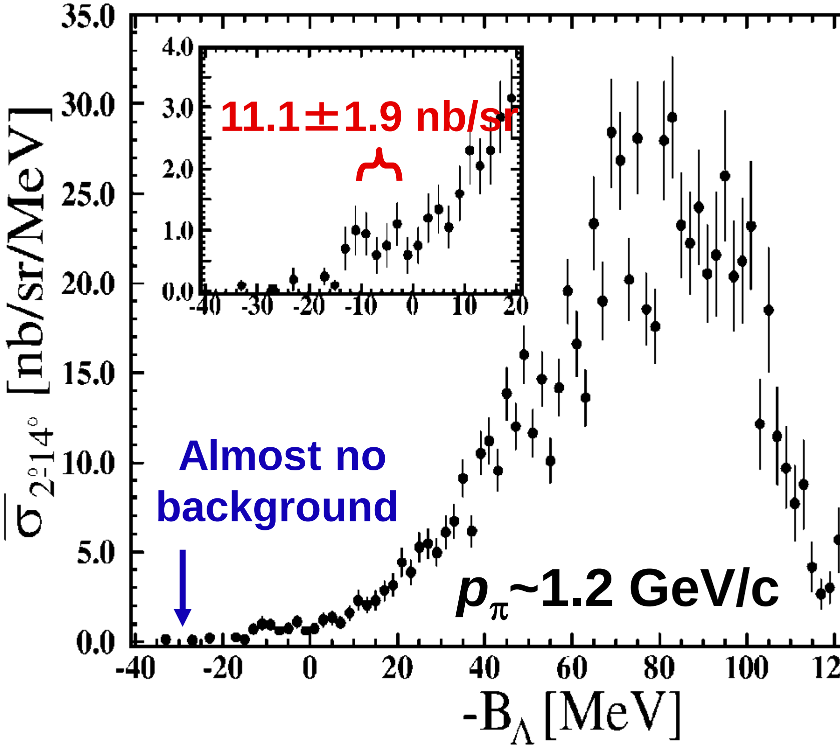
=> How large mixing in n-rich hypernuclei?



=> Effect to Λ appearance in n star?

$^{10}B(\pi^-, K^+)\,^{10}_{\Lambda}Li$

PRL 94 (2005) 052502



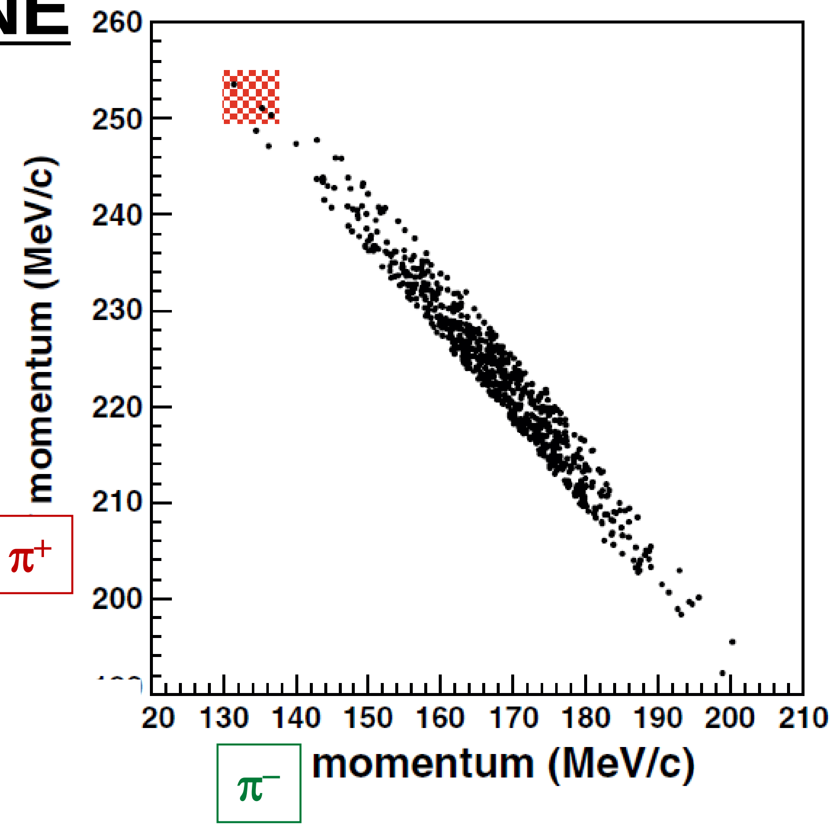
$^{6}_{\Lambda}$H from FINUDA@DAΦNE

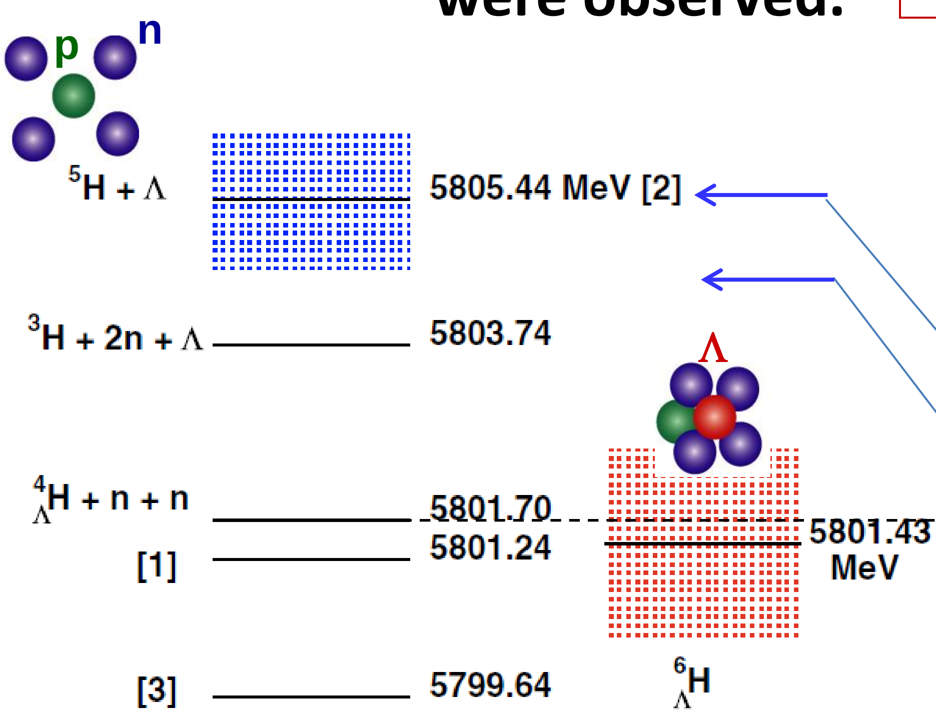
M. Agnello et al., PRL 108 (2012) 042501

K^-(stop) + ^{6}Li -> $^{6}_{\Lambda}$H + π^+

$^{6}_{\Lambda}$H -> ^{6}He + π^-

3 events of bound $^{6}_{\Lambda}$H were observed.



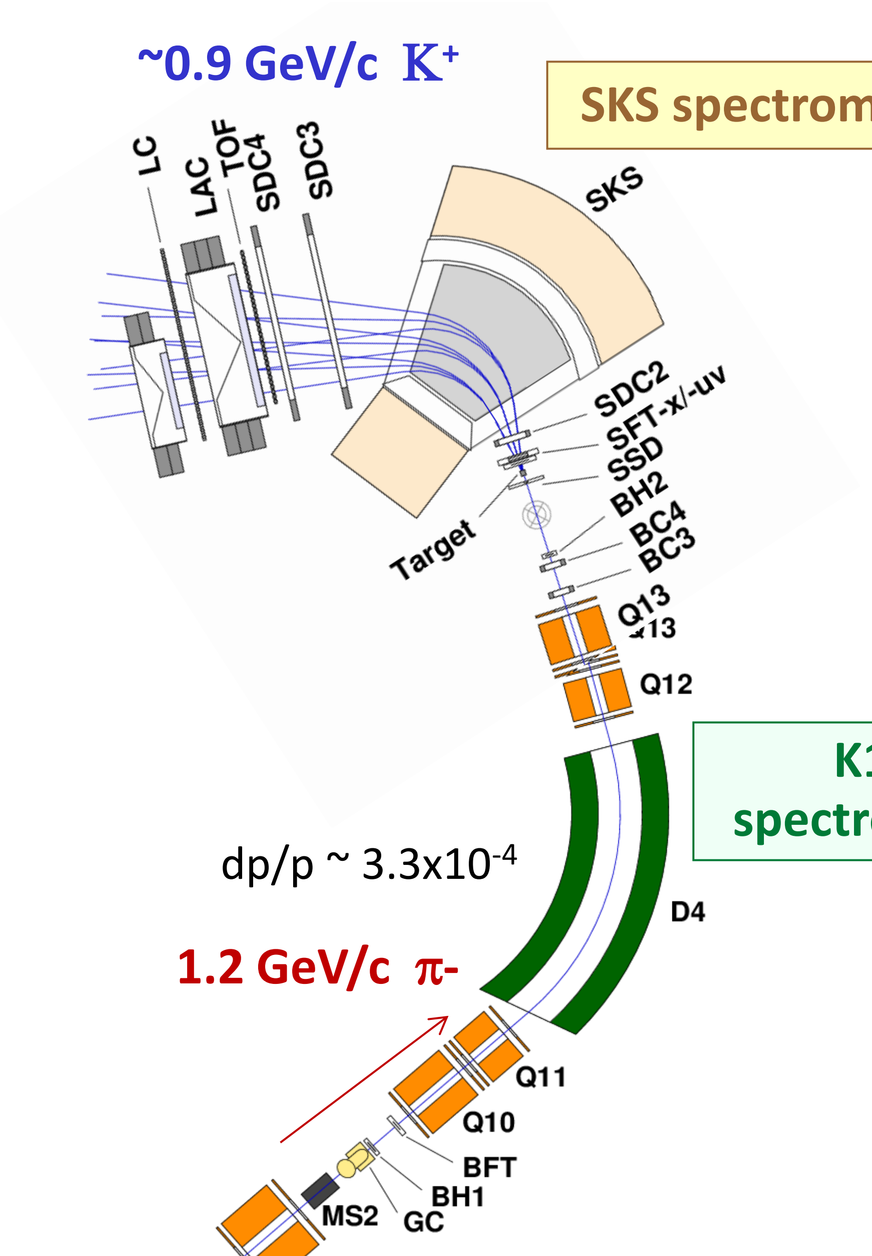


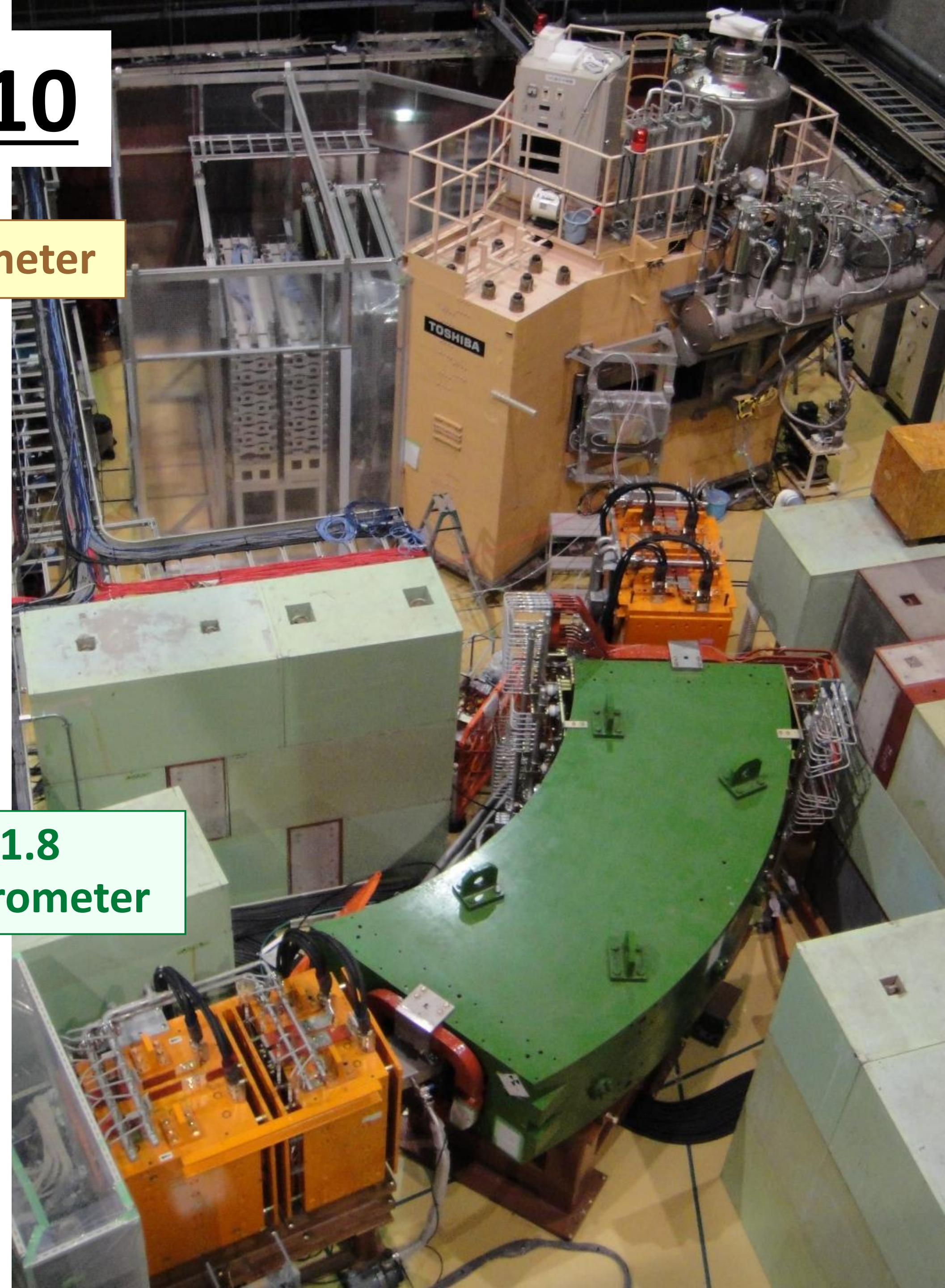
Hiyama et al.
NP A908 (2013) 29-39

No bound state for ^{5}H mass within the error bar

^{5}H mass should be measured

Setup of J-PARC E10





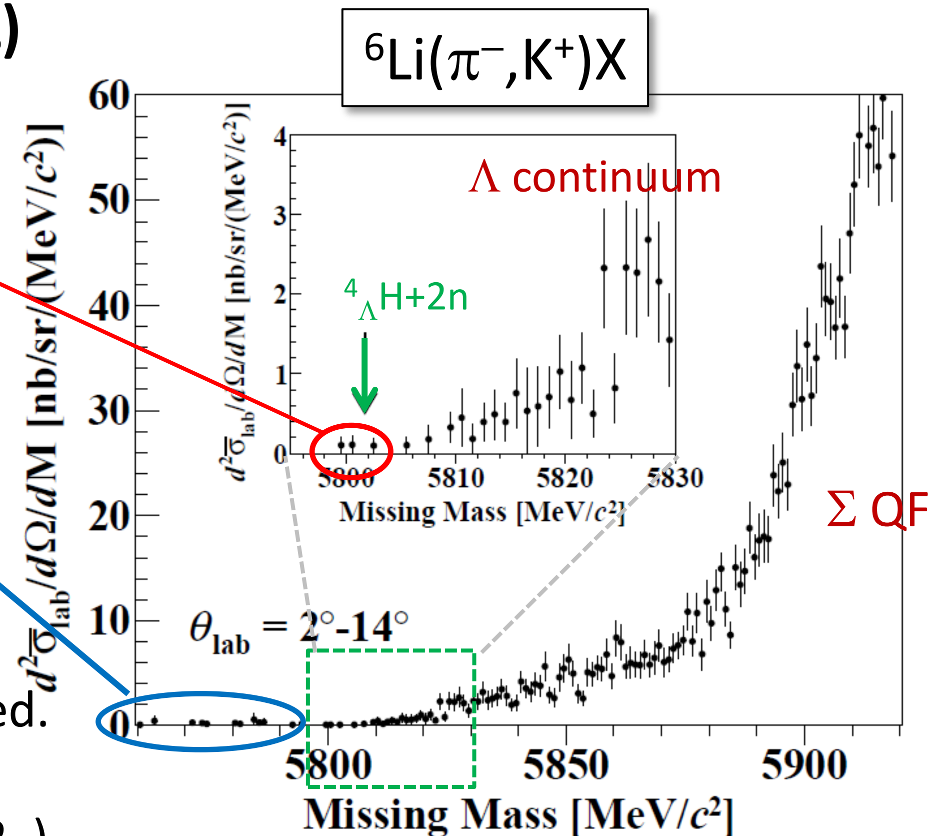
Results

Sugimura et al.
Phys. Lett. B729 (2014) 39

- **No peak observed in the missing mass spectrum**
- **$d\sigma_{2^\circ\text{-}14^\circ}/d\Omega$ < 1.2 nb/sr (90% CL)**

3 events around
$^{4}_{\Lambda}$H+2n threshold

Expected number of
background is ~2 events



Much lower than KEK E521
^{10}B (π^-,K$^+$)$^{10}_{\Lambda}$Li :
$d\sigma_{2^\circ\text{-}14^\circ}/d\Omega$ ~ 11 nb/sr

Mass res. 3.2 MeV/c^2 (FWHM)
Sys. Error ±1.26 MeV/c^2

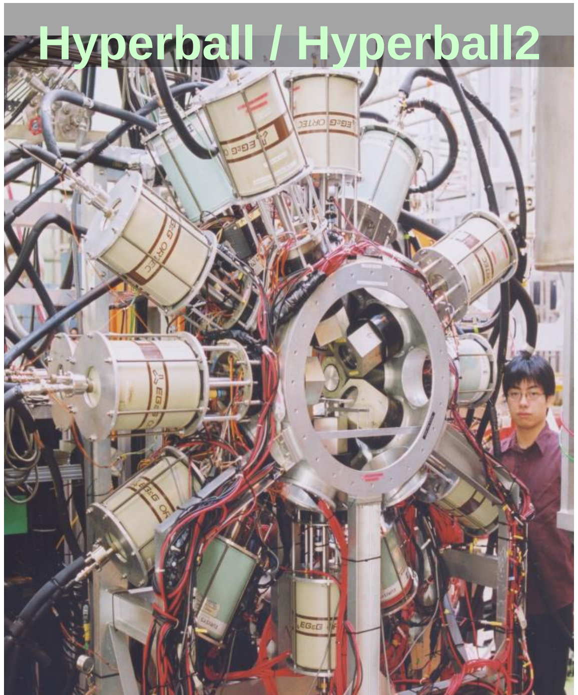
■ Production should be theoretically studied.
^{10}B -> $^{10}_{\Lambda}$Li : $(p3/2_p)^2$ -> $(p3/2_n)(s1/2_\Lambda)$
^{6}Li -> $^{6}_{\Lambda}$H : $(p3/2_p)(s1/2_p)$-> $(p3/2_n)(s1/2_\Lambda)$

■ Continuum fitted by Harada's potential model calc.
-> Σ potential strongly repulsive

■ Next target: ^{9}Be (π^-,K$^+$)$^{9}_{\Lambda}$He. When can we run??

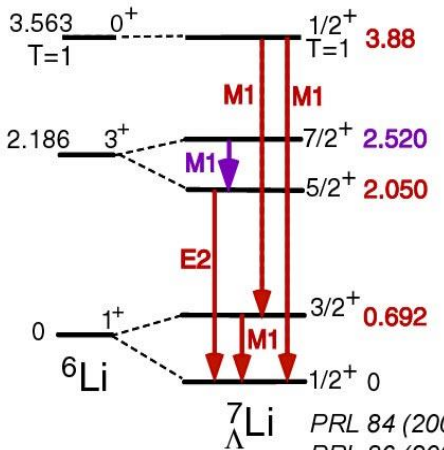
3. γ–ray spectroscopy

Hypernuclear γ-ray data



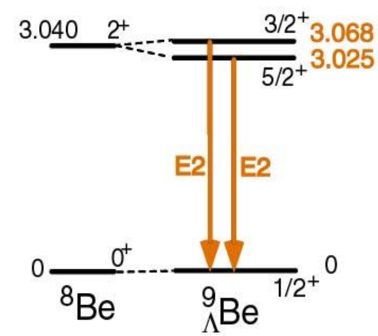
PLB 83 (1979) 252

^{7}Li (π^{+},K^{+}γ) KEK E419



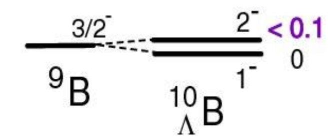
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

^{9}Be (K^{-},π^{-}γ) BNL E930('98)



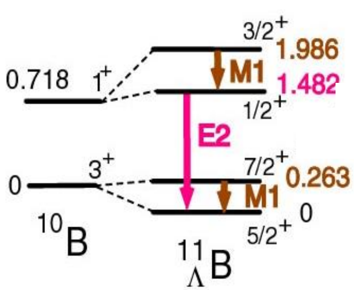
PRL 88 (2002) 082501
NPA 754 (2005) 58c

^{10}B (K^{-},π^{-}γ) BNL E930('01)



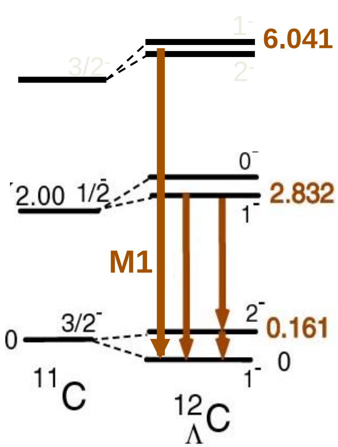
NPA 754 (2005) 58c

^{11}B (π^{+},K^{+}γ) KEK E518



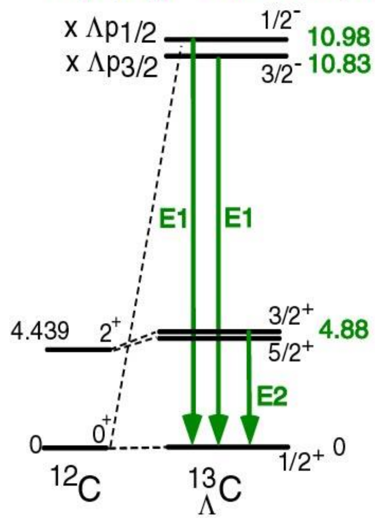
NPA 754 (2005) 58c

^{12}C (π^{+},K^{+}γ) KEK E566



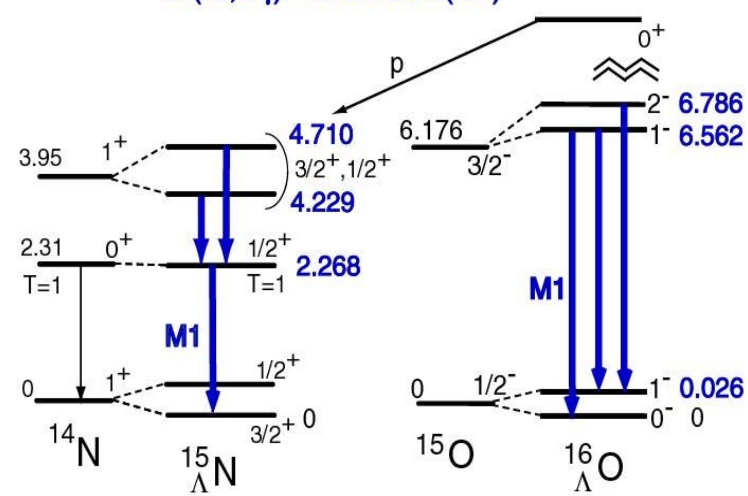
EPJ A33 (2007) 243
NPA835 (2010) 422

^{13}C (K^{-},π^{-}γ) BNL E929 (NaI)



PRL 86 (2001) 4255
PRC 65 (2002) 034607

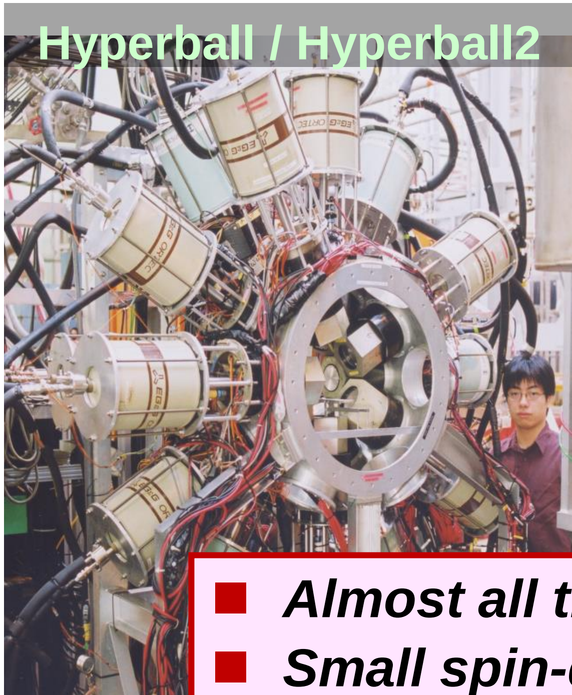
^{16}O (K^{-},π^{-}γ) BNL E930('01)

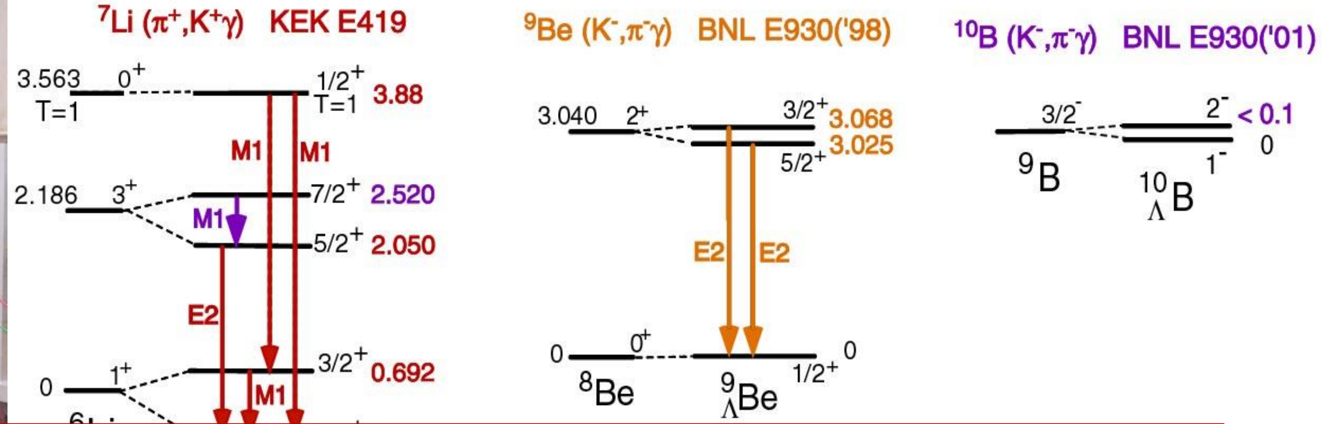


PRC 77 (2008) 054315

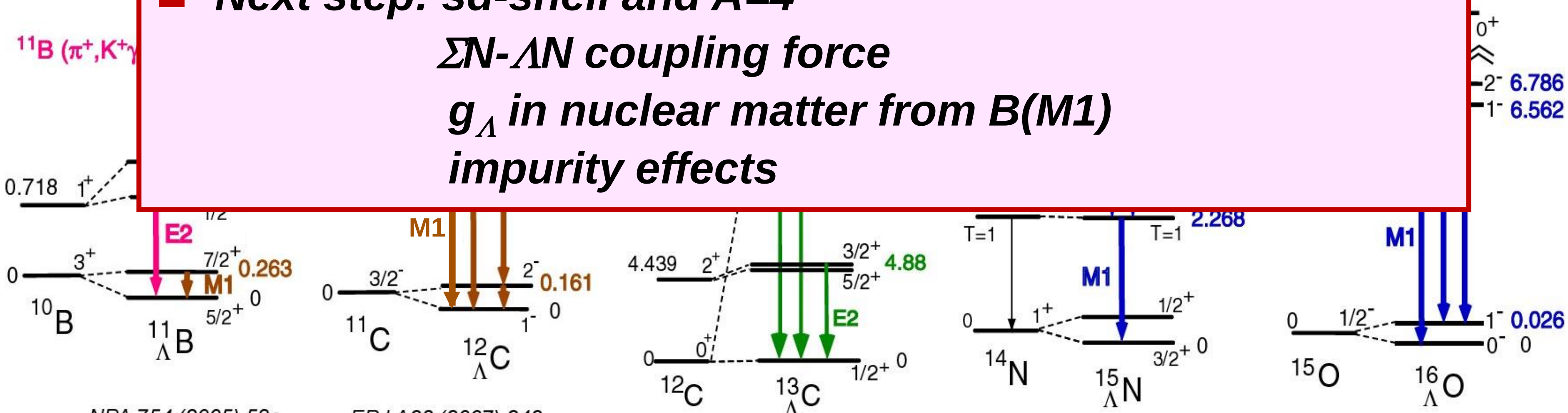
PRL 93 (2004) 232501
EPJ A33 (2007) 247

Hypernuclear γ-ray data





- ***Almost all the p-shell hypernuclei have been studied.***
- ***Small spin-dependent ΛN forces have been established quantitatively.***
- ***Next step: sd-shell and A=4***
  - ***ΣN-ΛN coupling force***
  - ***g_Λ in nuclear matter from B(M1)***
  - ***impurity effects***



NPA 754 (2005) 58c

EPJ A33 (2007) 243
NPA835 (2010) 422

PRL 86 (2001) 4255
PRC 65 (2002) 034607

PRC 77 (2008) 054315

PRL 93 (2004) 232501
EPJ A33 (2007) 247

Hyperball-J for γ-spectroscopy (E13)

PWO
Fast background suppressor

Ge detector

Pulse-tube refrigerator
~70K (c.f. 92K w/LN2)

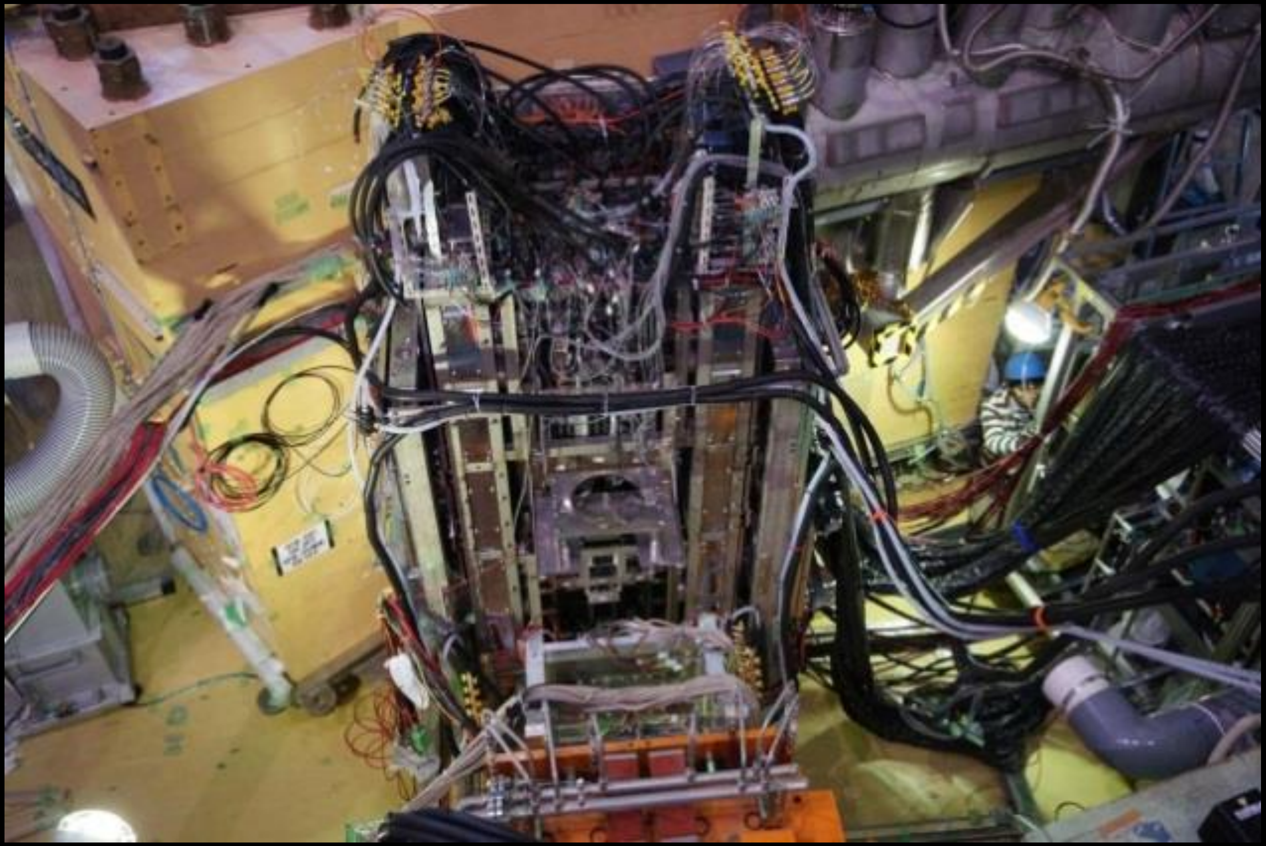
ΔE= 3.1(1) keV at 1.33 MeV

E13 program

- $^{4}_{\Lambda}$He (Charge symmetry breaking)
- $^{19}_{\Lambda}$F (ΛN interaction in sd-shell)
- $^{10}_{\Lambda}$B, $^{11}_{\Lambda}$B (ΛN-ΣN interaction)
- $^{7}_{\Lambda}$Li (B(M1) for g_{Λ} in nucleus)

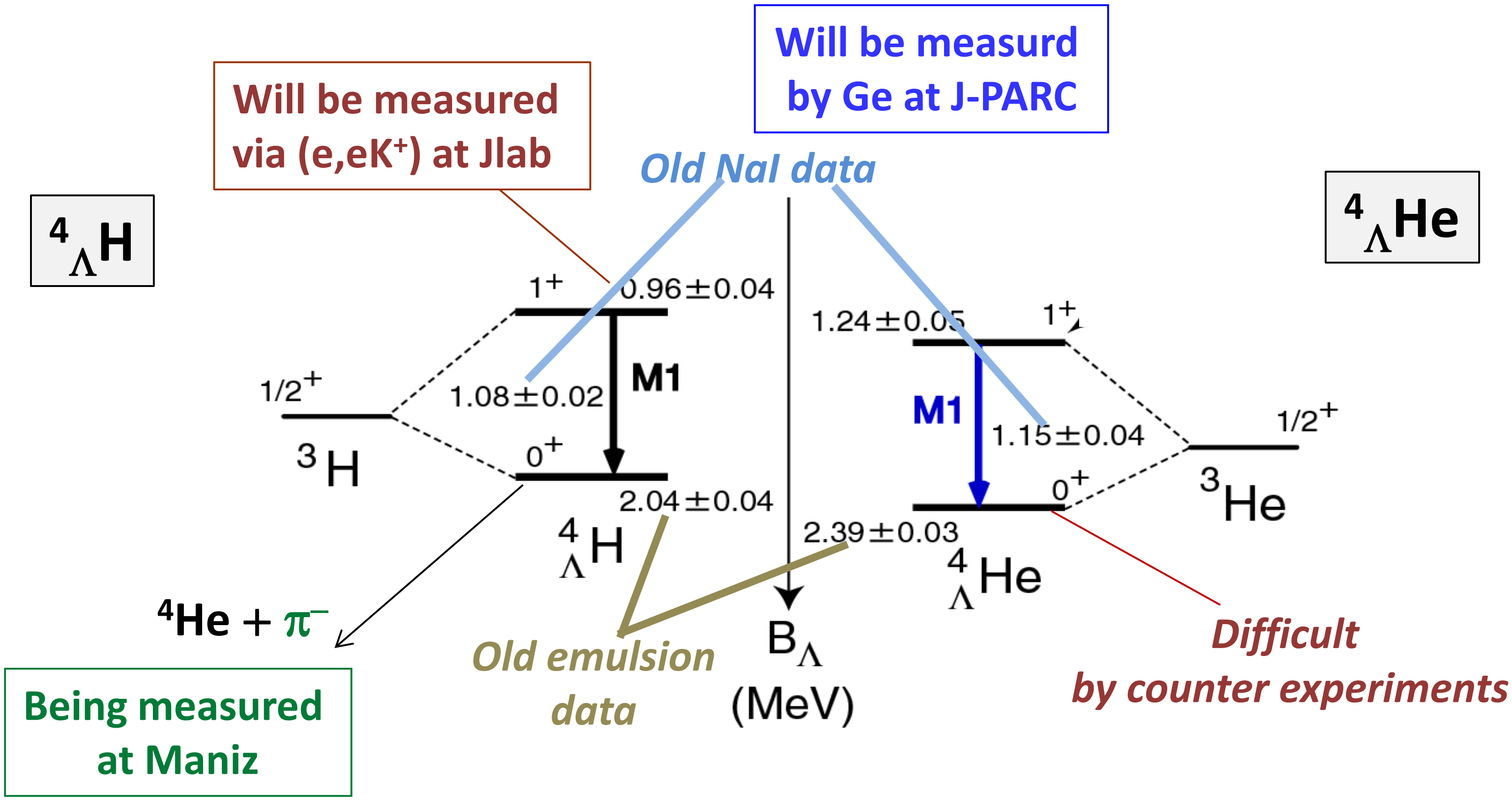
Everything except for HF target is ready. Run from Jan. 2015.

Hyperball-J
installed in front of SKS magnet at K1.8

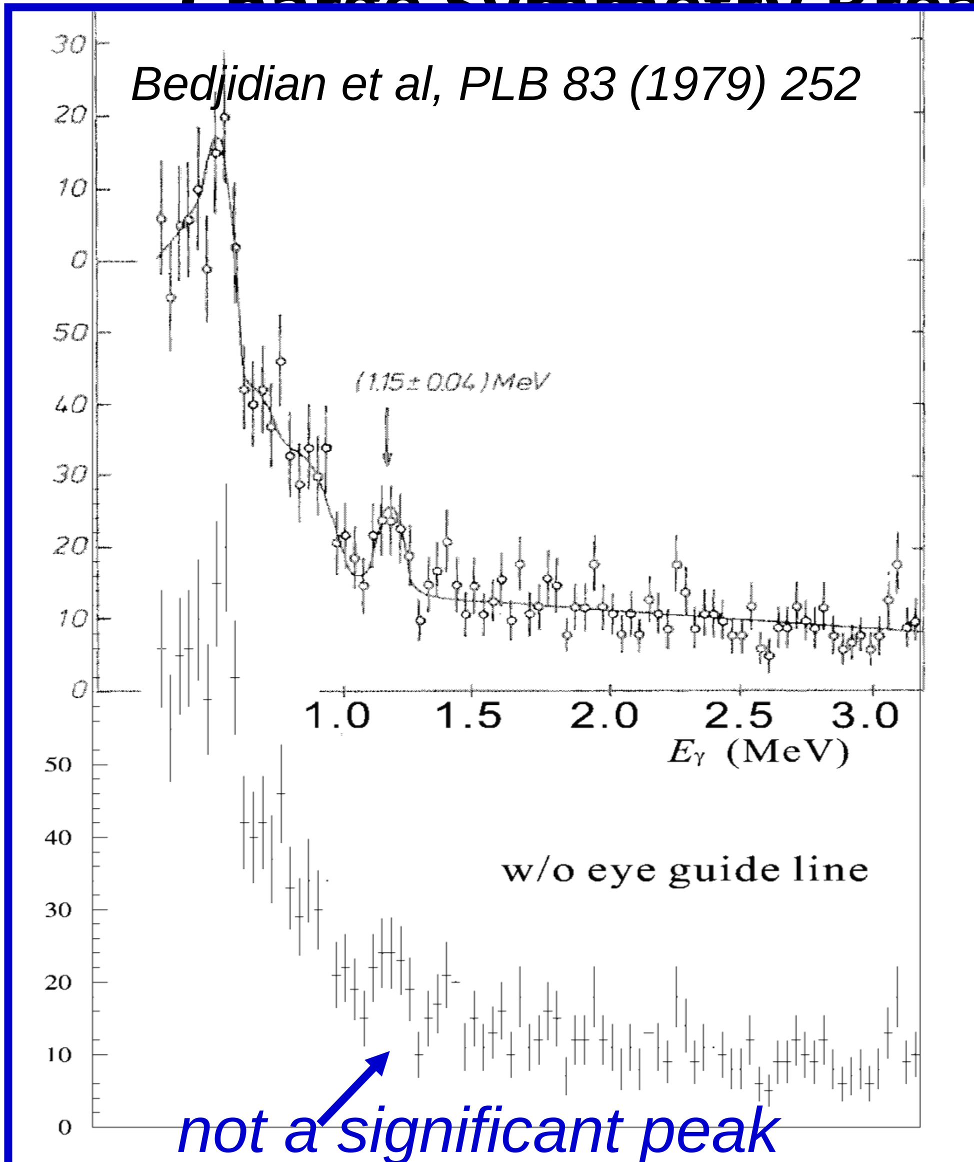


E13: started but suspended due to the radiation accident since the end of May, 2013

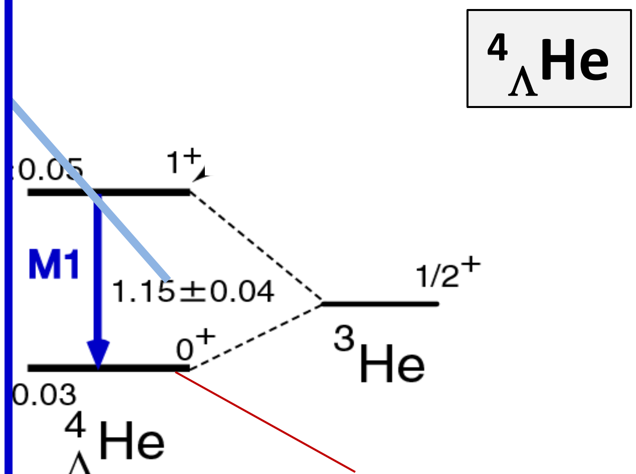
Experimental approaches to Charge Symmetry Breaking puzzle in A=4



Experimental approaches to Charge Symmetry Breaking puzzle in A=4



measurd
at J-PARC



Difficult
by counter experiments

He target run

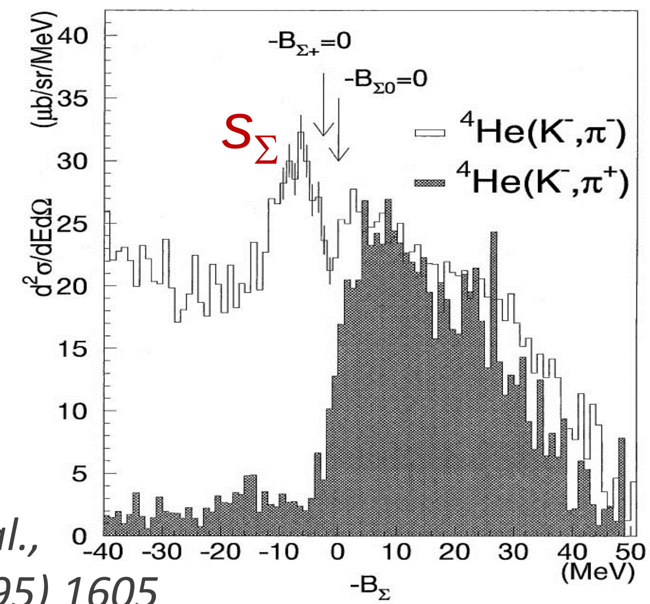
^{4}He target (K^{-},π^{-}) 1.5 GeV/c

- $^{4}_{\Lambda}$He γ spectroscopy ($1^{+} \rightarrow 0^{+}$)
  -> Confirm (deny) CSB effects

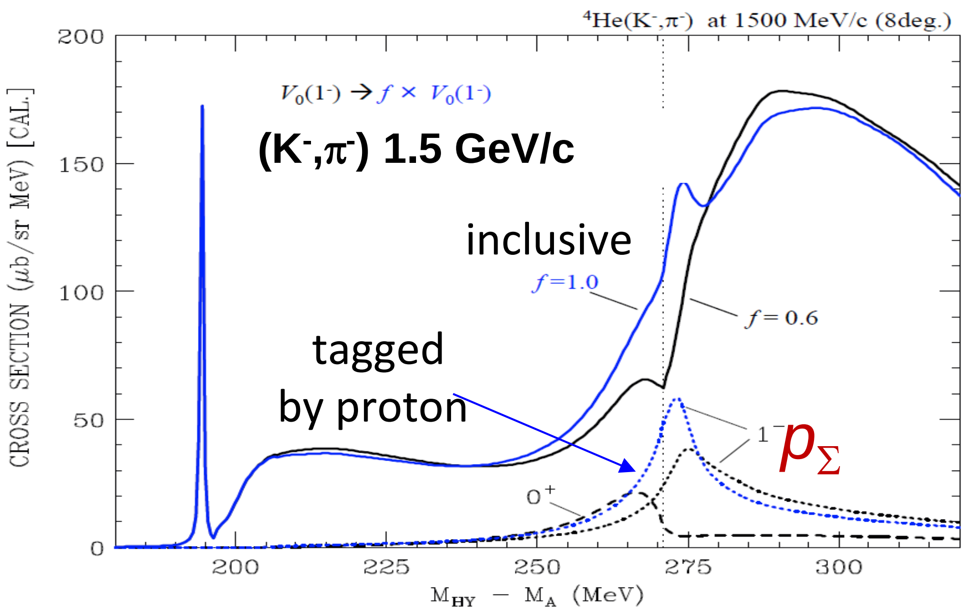
(Byproduct)

- $^{4}_{\Lambda}$He(1^{+}) cross section:
  First measurement of spin-flip states
- $^{4}_{\Sigma}$He production at 1.5 GeV/c
  -> s_{Σ} (0^{+}) and p_{Σ} (1^{-}) states can be observed by tagging ΣN->ΛN
  ~ 40,000 inclusive events of $^{4}_{\Sigma}$He

(K^{-},π^{-}) 0.6 GeV/c



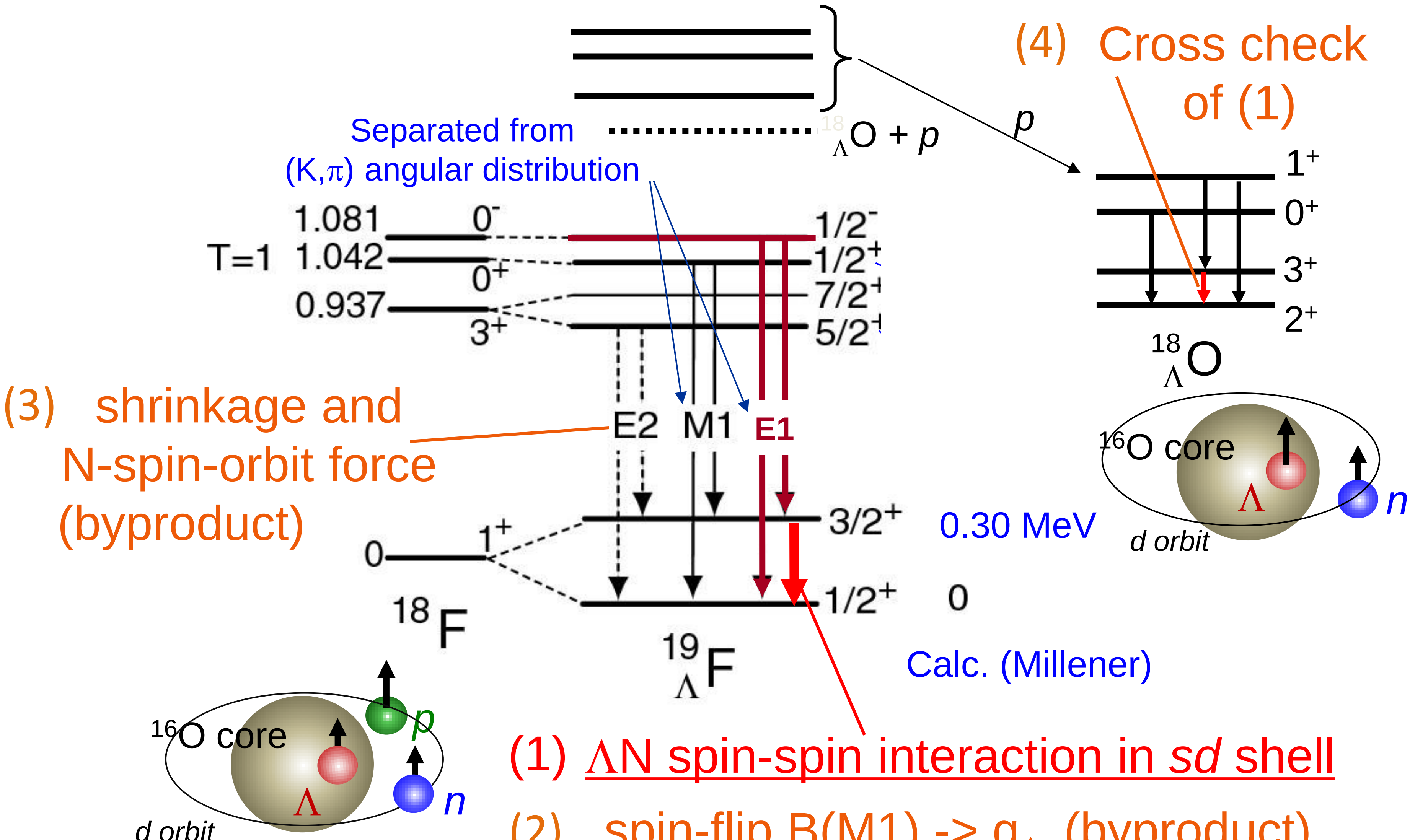
Nagae et al., PRL 80(1995) 1605



T. Harada, priv. comm.

$^{19}_{\Lambda}$F spectroscopy

The first study of sd-shell hypernuclei



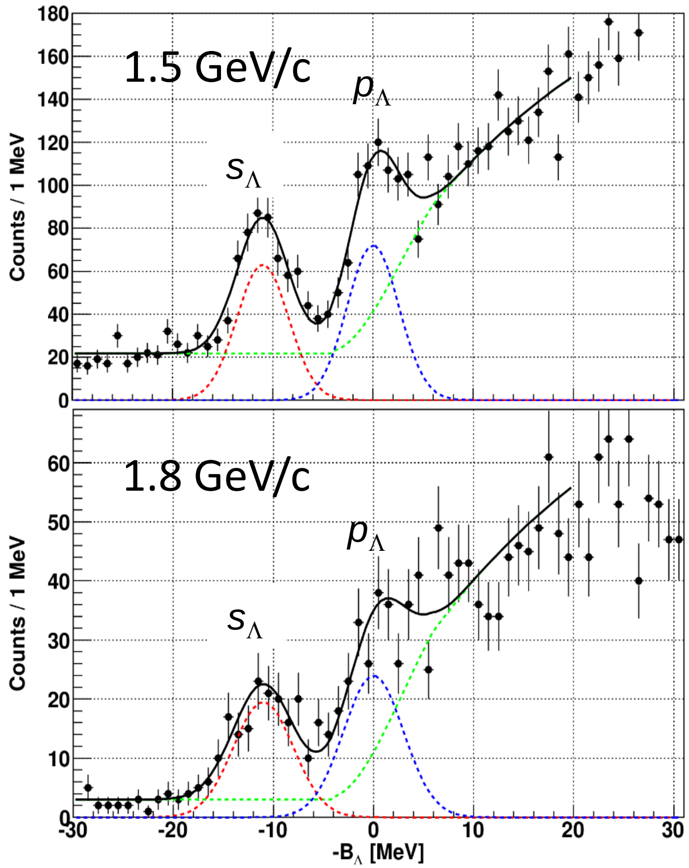
(1) ΛN spin-spin interaction in *sd* shell

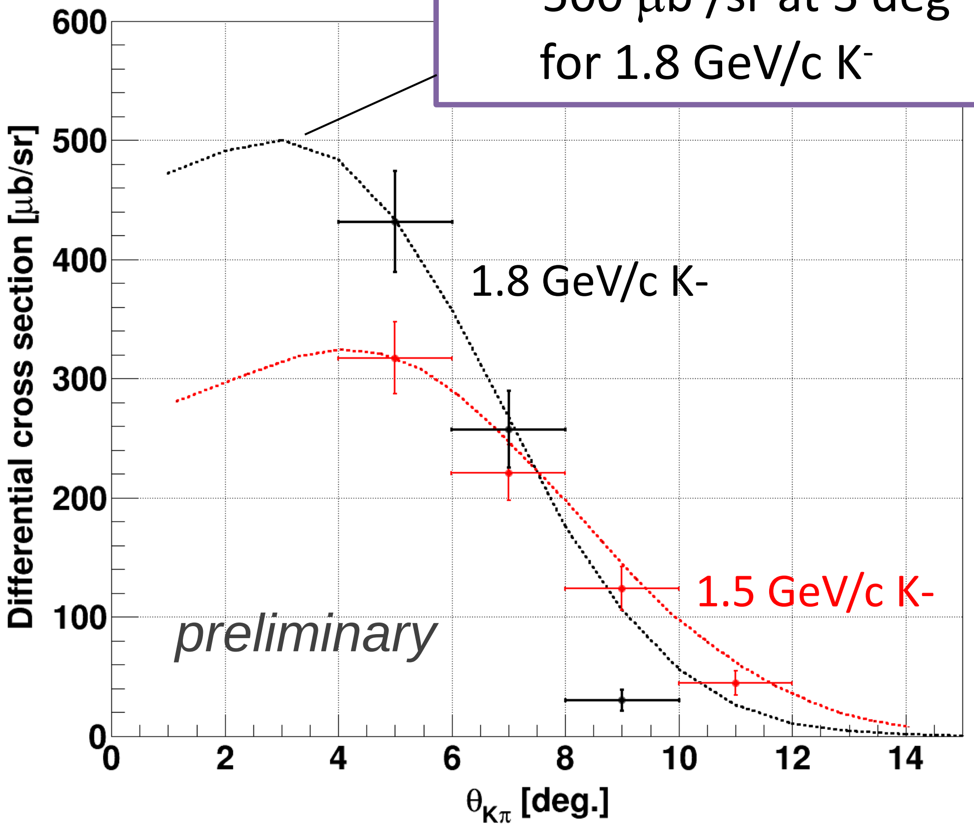
(2) spin-flip B(M1) -> g_{Λ} (byproduct)

E13 commissioning – (K⁻,π⁻) cross sections

2013 May, E13 commissioning data

$^{12}C\ (K^-,\pi^-)\ ^{12}_{\Lambda}C$





4. Σ-p scattering

What we know about Σ-N force

$^{4}_{\Sigma}$He bound state

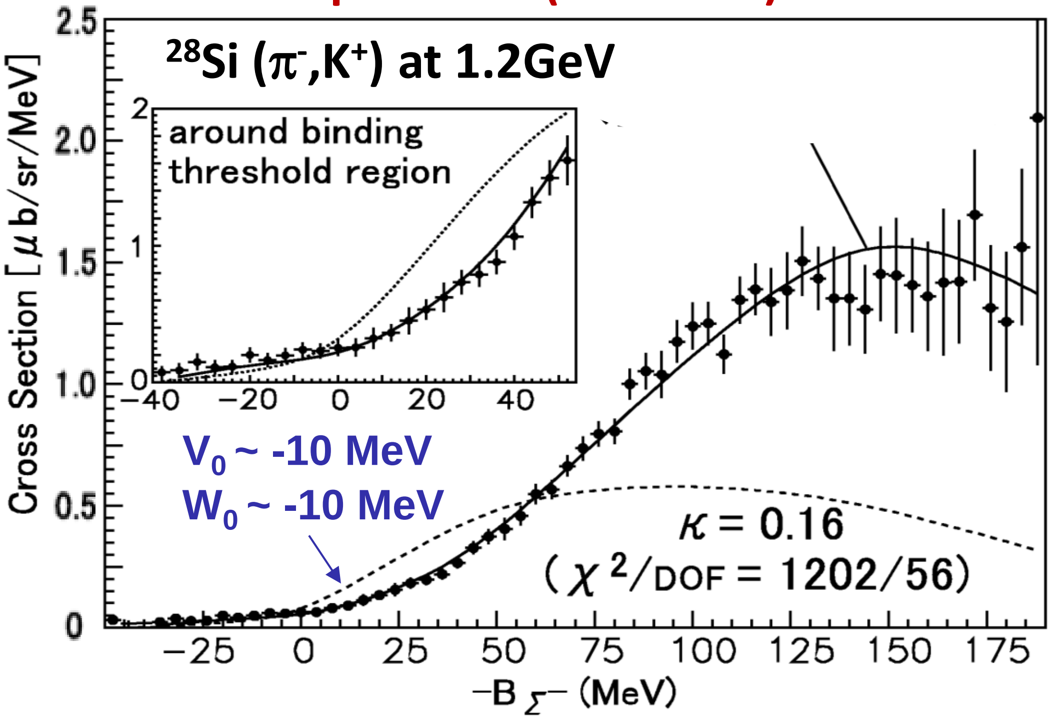
suggests **large spin-isospin dependence**

(I,S) = (3/2,0), (1/2,1) attractive

(3/2,1), (1/2,0) repulsive

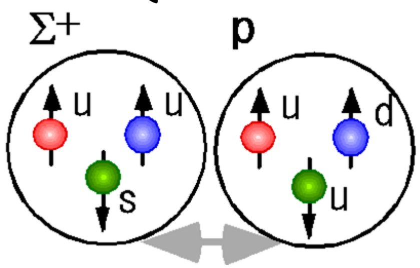
-- Consistent with meson exchange models

Σ^{-}-^{28}Si Nuclear potential (KEK E438)



PRL 87(2002) 072301

- Strong repulsion comes from Pauli effect between quarks?
  Quark Cluster Model
  Lattice QCD



ΣN (I,S) = (3/2,1)

- Σ's never appear in n-stars?

High statistics

Σ^{+}p/ Σ^{-}p scattering experiment

J-PARC E40

-> **Strongly repulsive** potential (U~ +30 MeV)

How repulsive are (I,S) = (3/2,1), (1/2,0) channels?

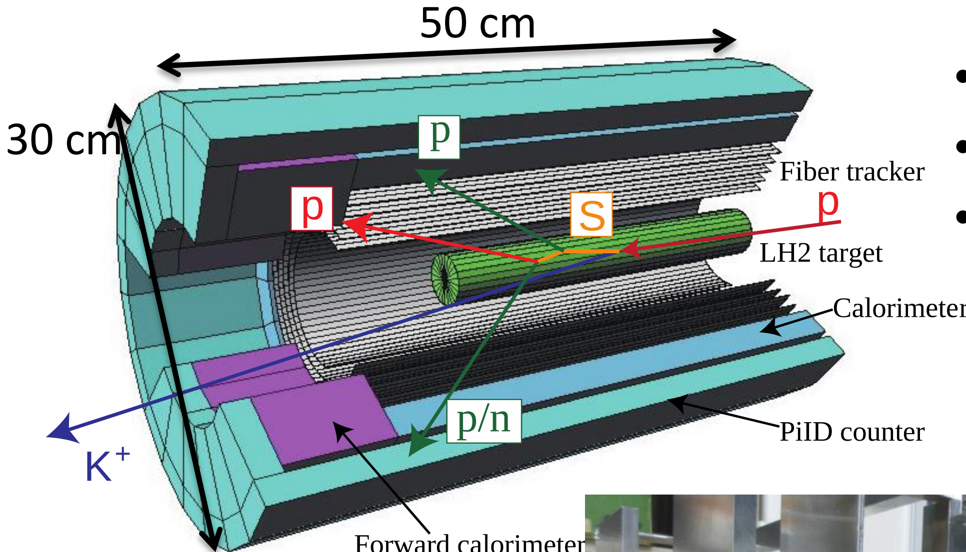
J-PARC E40 (Miwa): $\Sigma^{\pm}p$ scattering experiment

($\pi^{\pm}$, K^{+}) reaction -> $\Sigma^{\pm}$ momentum vector

Measure *E, ΔE* of scatterd proton (+ Σ decay π/p)

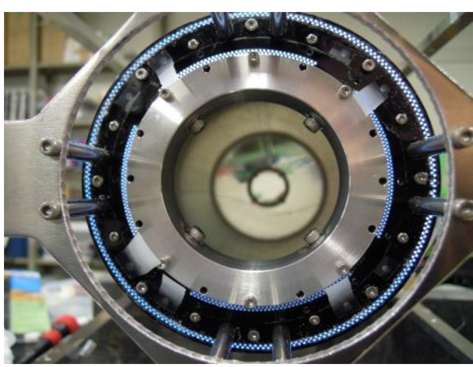
⇒ Identify scattering events from kinematics without measuring the vertex image

⇒ High statistics



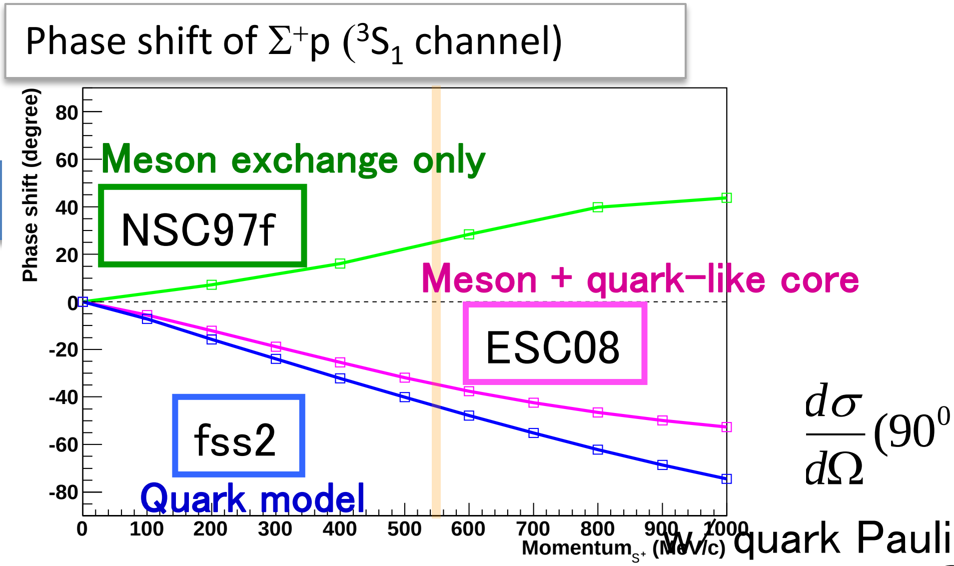
- Ultra-fast fiber tracker w/MPPC readout
- Calorimeter (BGO)
- Liq. H_2 target

R&D successfully completed.



Slide by Koji Miwa

Σ^+p interaction: Phase shift of $^3S_1$ channel

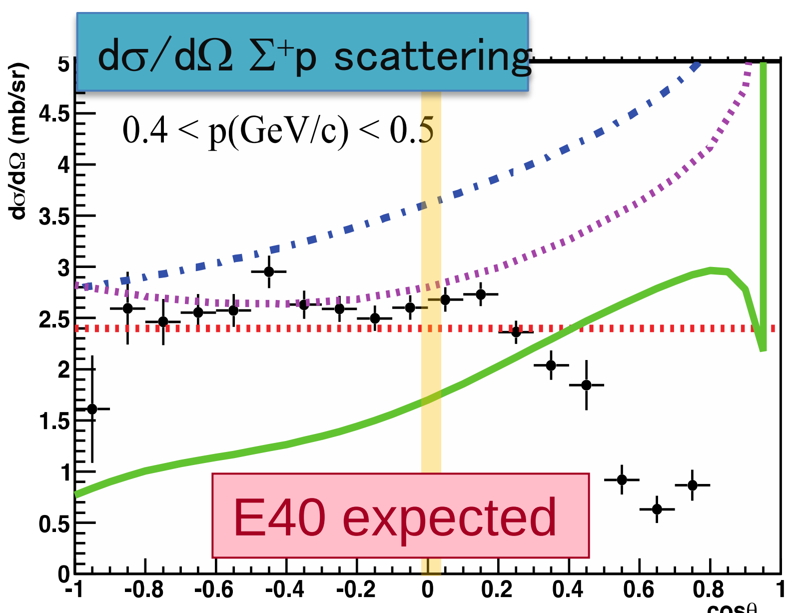


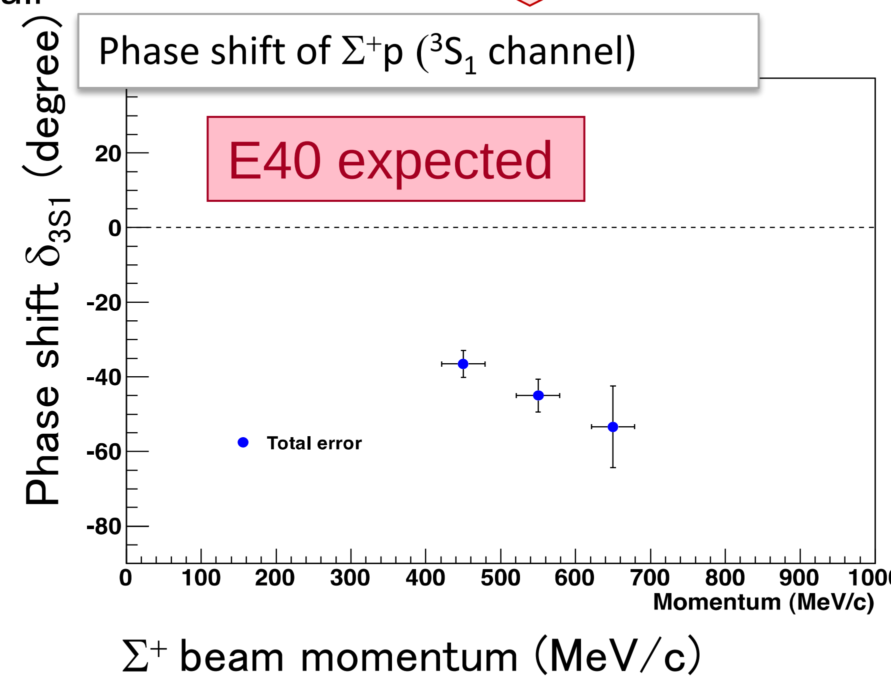
- Energy dependence of δ_{3S1} from $d\sigma/d\Omega(90^o)$

Negligibly small

Almost model-independent

$$\frac{d\sigma}{d\Omega}(90^0) = \boxed{\frac{1}{4}\frac{1}{k^2}\sin^2\delta_{1S0}} + \boxed{\frac{3}{4}\frac{1}{k^2}\sin^2\delta_{3S1}} + \boxed{(\text{higher waves})}$$



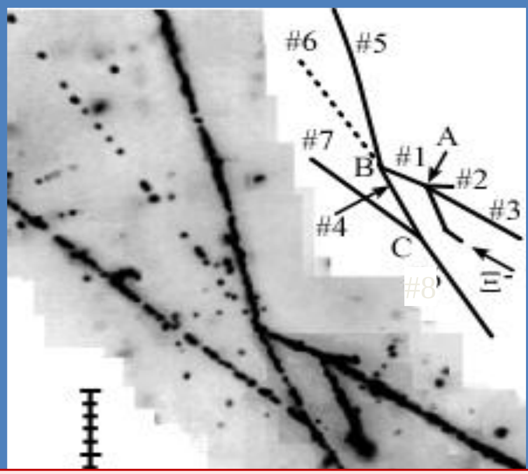


5. S=-2 systems (E07)

Slide by Nakazawa

ΛΛ hypernuclei (KEK E373)

Nagara event



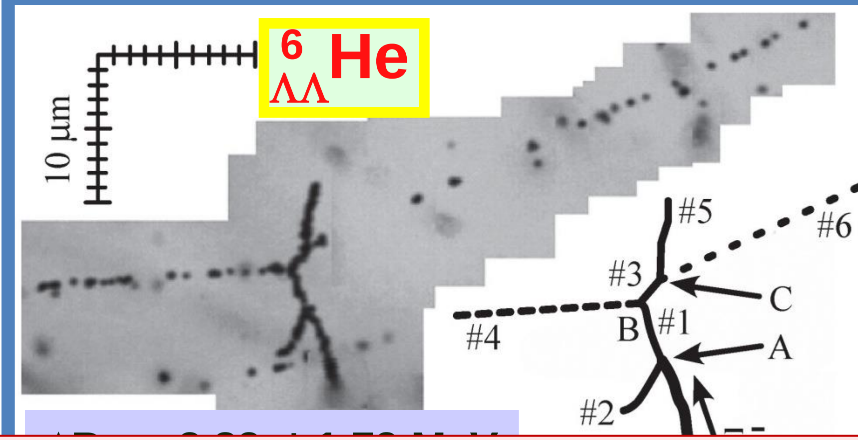
$^{6}_{\Lambda\Lambda}$He

(unique and accurate)

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

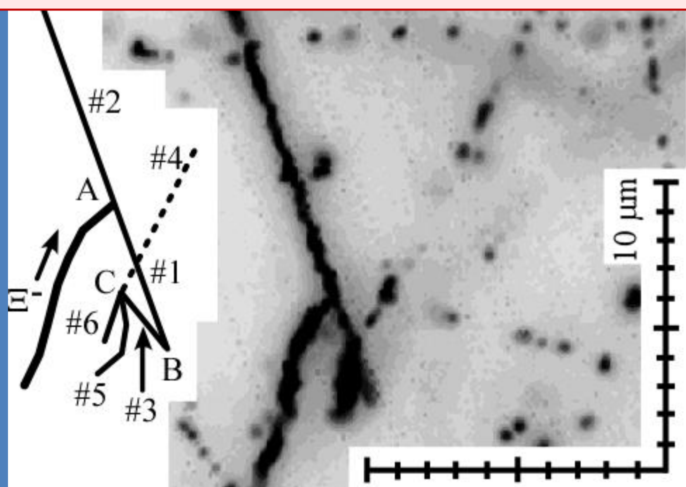
p

Mikage event



$^{6}_{\Lambda\Lambda}$He

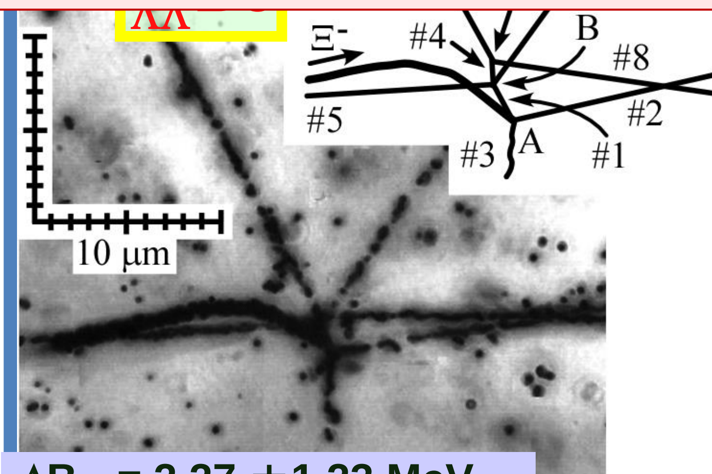
Overall scanning method has been successfully developed.
Reanalysis of E373 data – new events coming!



$^{10}_{\Lambda\Lambda}$Be*

(w/ theoretical help)

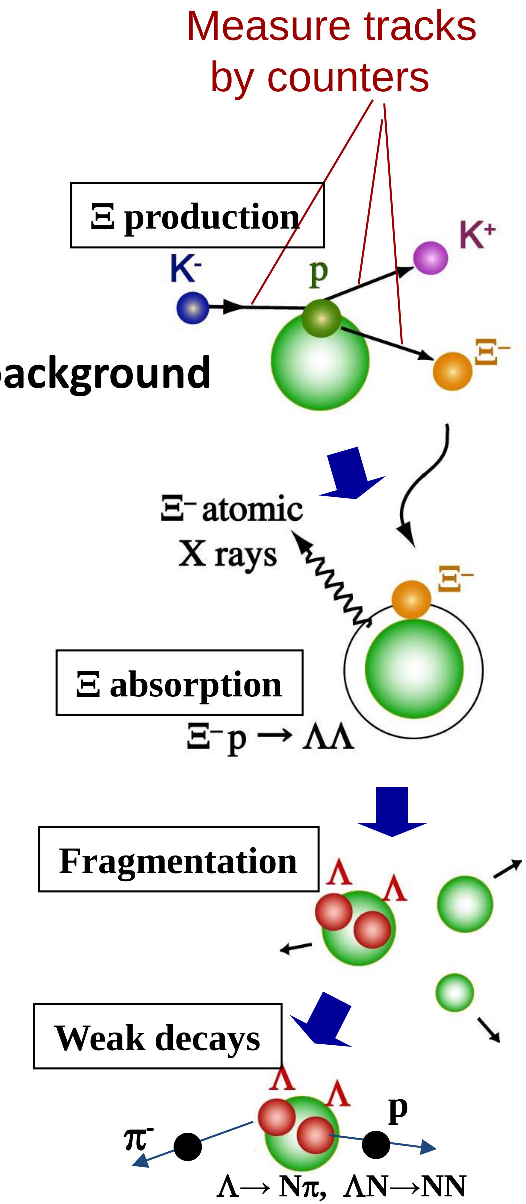
$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0(*Ex*)

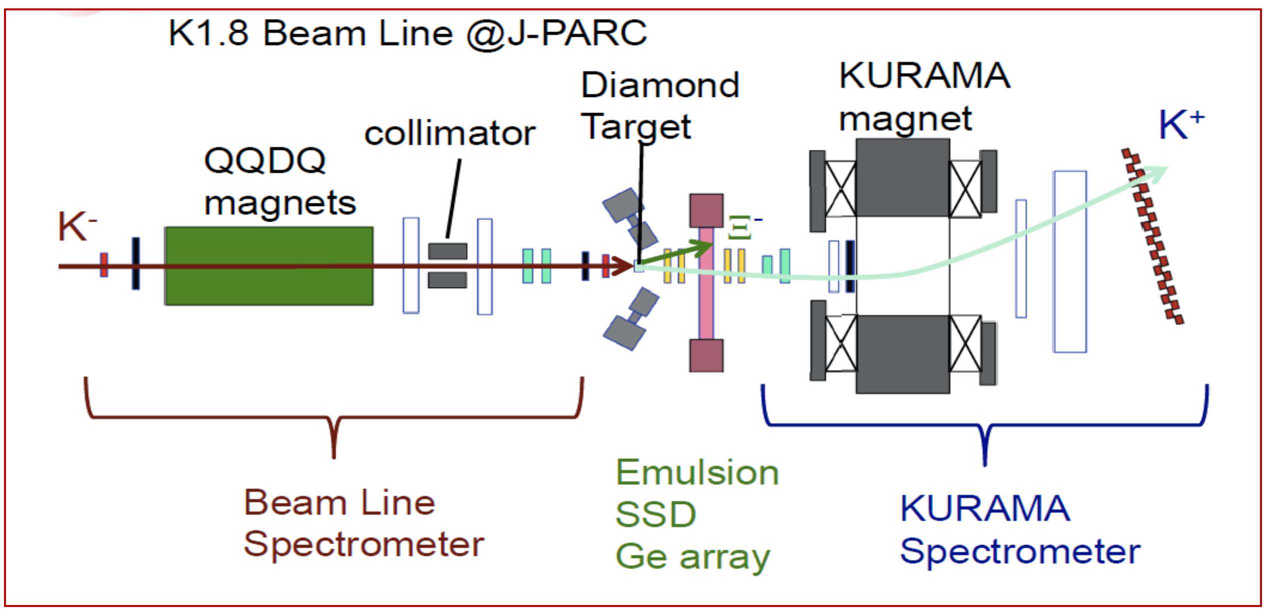


$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

J-PARC E07 (Nakazawa, Imai, Tamura) S=-2 Systems by emulsion

- Collect ~10^2 $\Lambda\Lambda$ hypernuclear events from ~10^4 Ξ^-_{stop}
  - Confirm $\Lambda\Lambda$ interaction strength
  - Λ–Λ correlation in nucleus from "$\Lambda\Lambda$" -> Σ^-p decay
- Measure Ξ^- -atomic X-rays with Ge detectors
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Stopped Ξ^- events identified from emulsion image –> no background

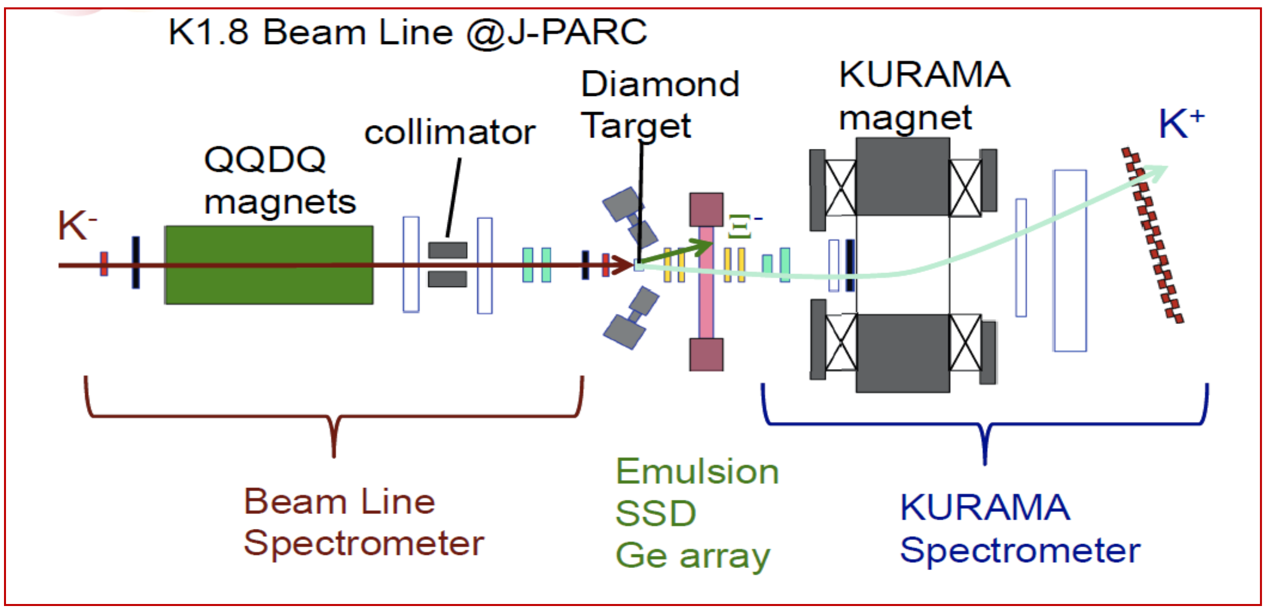


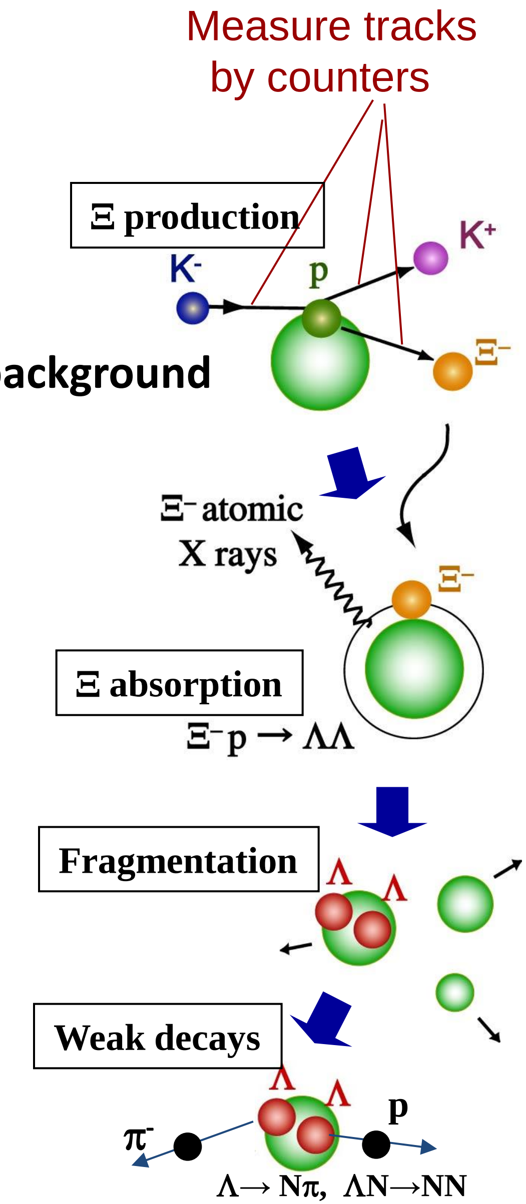


Emulsion and most of the counters ready
Change SKS -> KURAMA in the summer 2015

…stems by emulsion

…no background





Emulsion and most of the counters ready
Change SKS -> KURAMA in the summer 2015

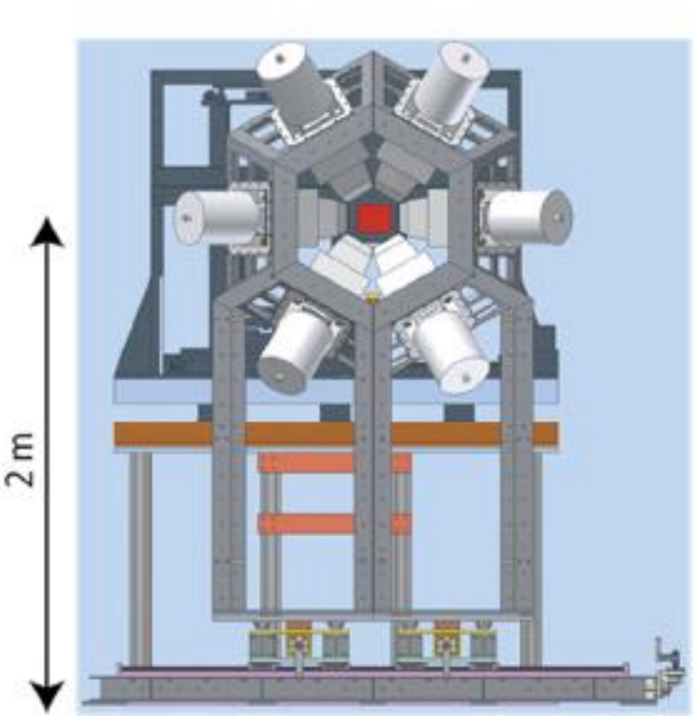
Expected Ξ- atomic X-ray spectrum (E07)

Shift: 30-100 peak events -> **stat. error ~ ±0.1--0.2 keV**

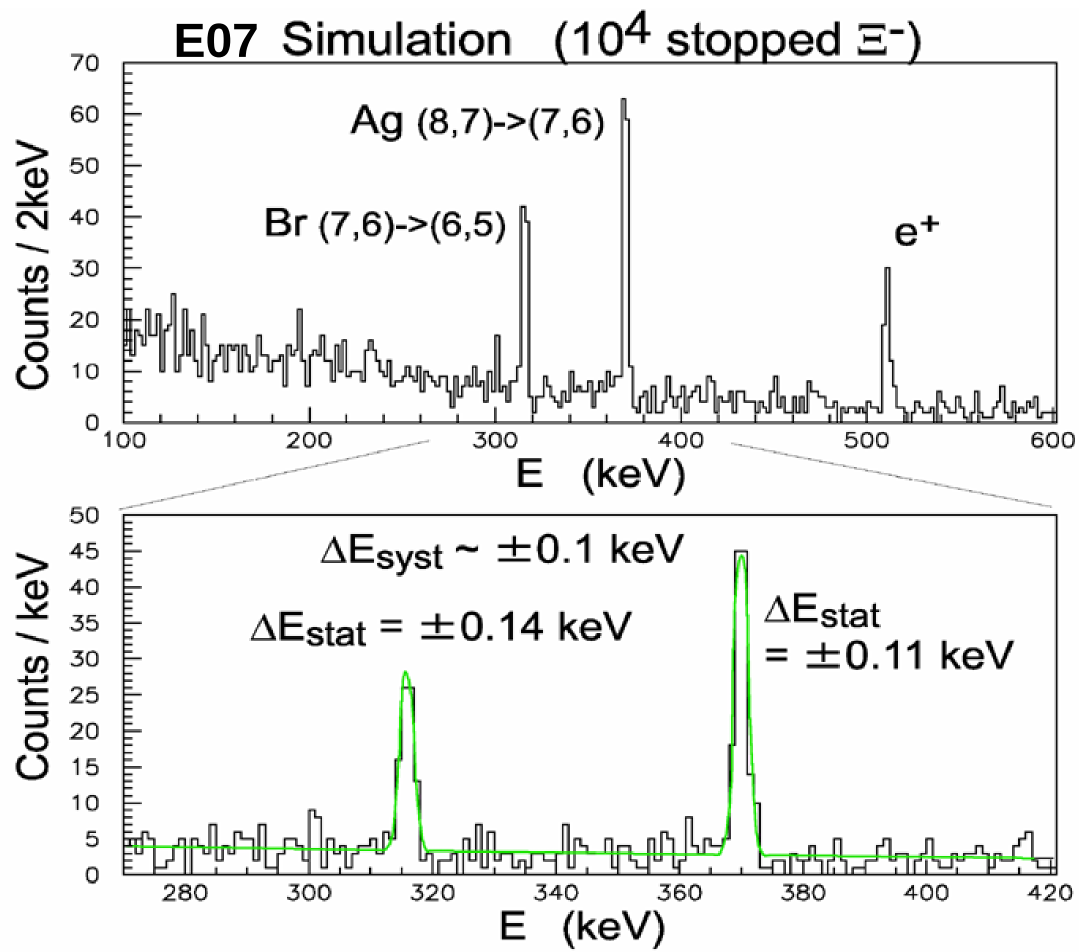
In-beam energy calibration using LSO counter -> **syst. error ~±0.1 keV**

Width: measureable if Γ > 1 keV

Expected shift ≲ 2 keV ***(Friedman, Gal)***

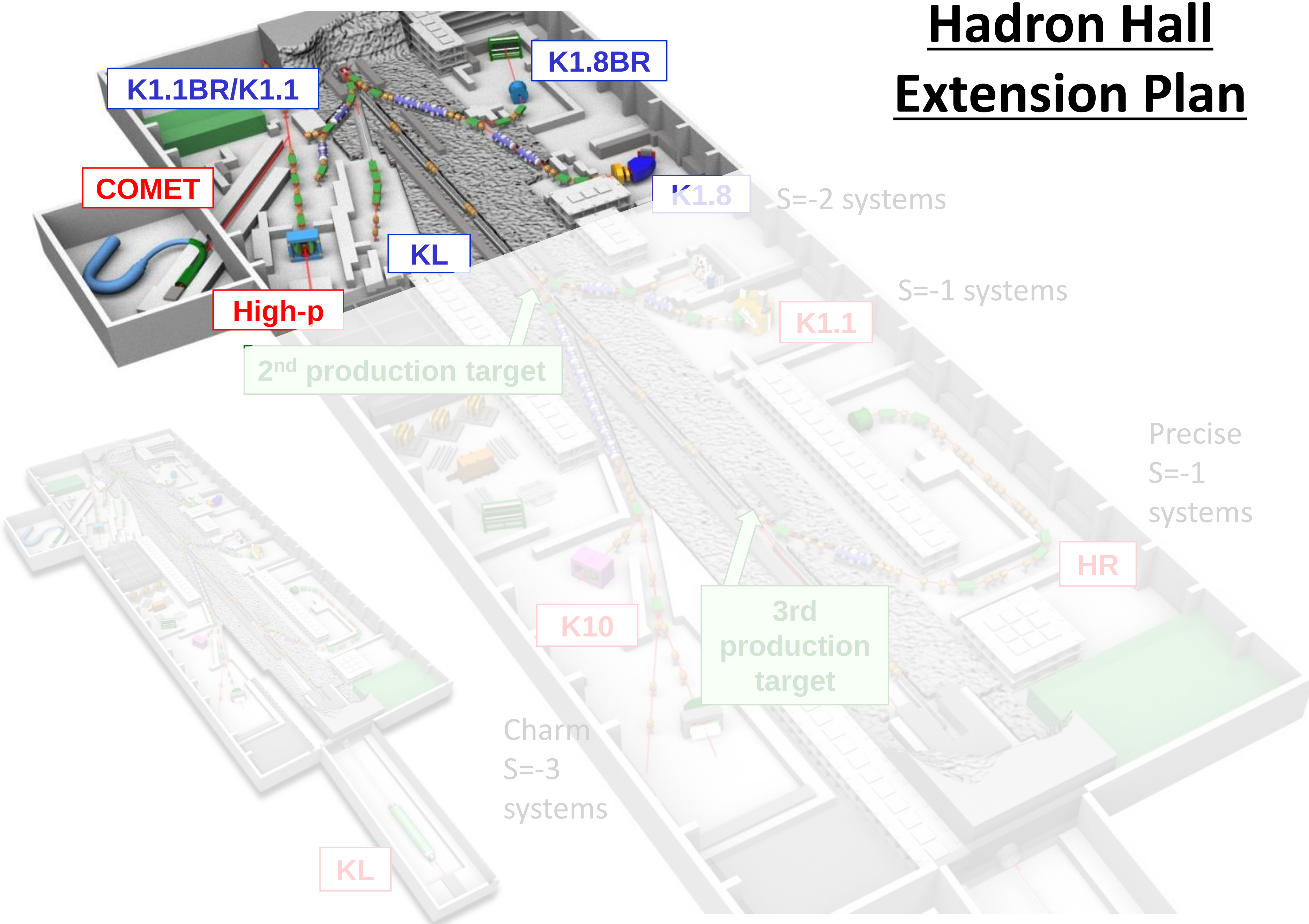


6 Clover Ge detectors
from Tohoku Univ.
Eff. ~3% @ 350 keV

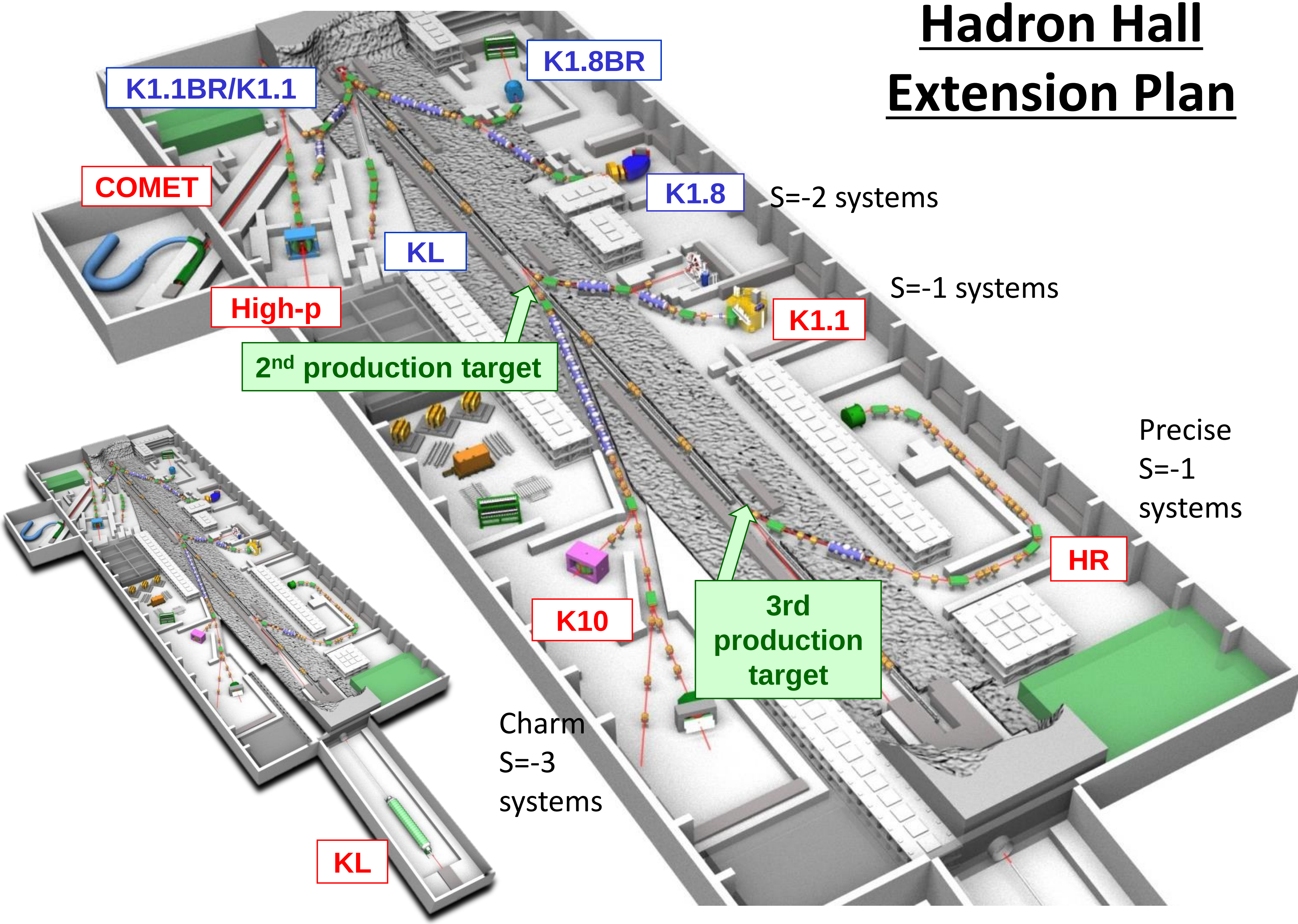


6. Future Plan of the Hadron Hall

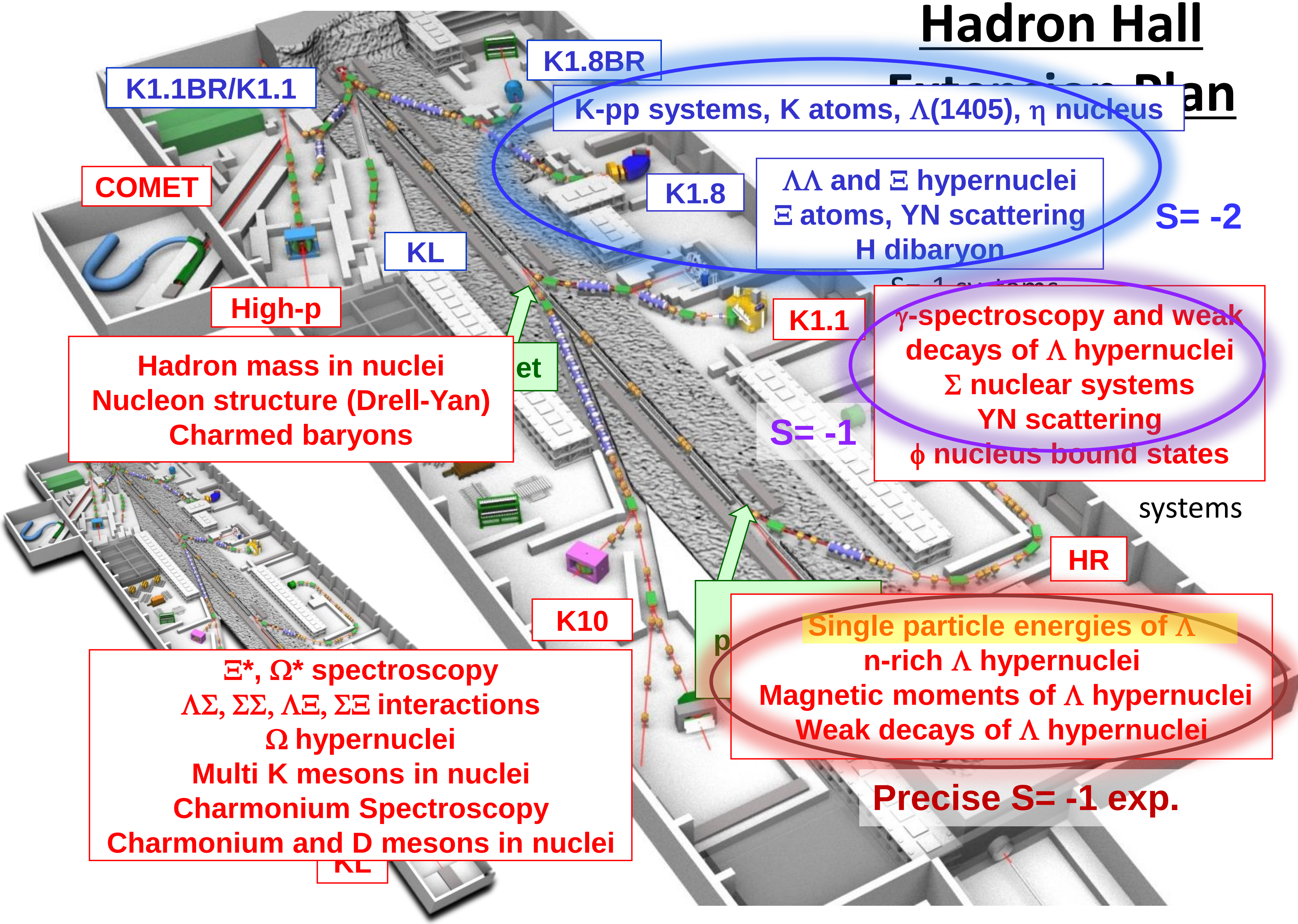
Hadron Hall Extension Plan



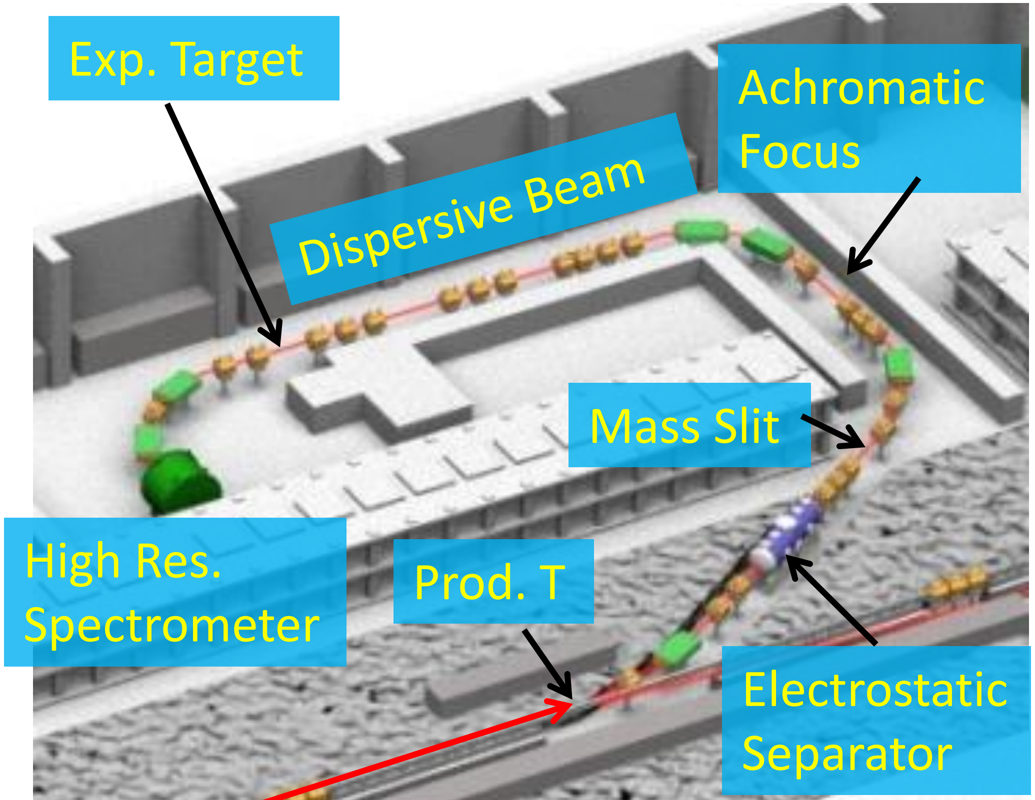
Hadron Hall Extension Plan



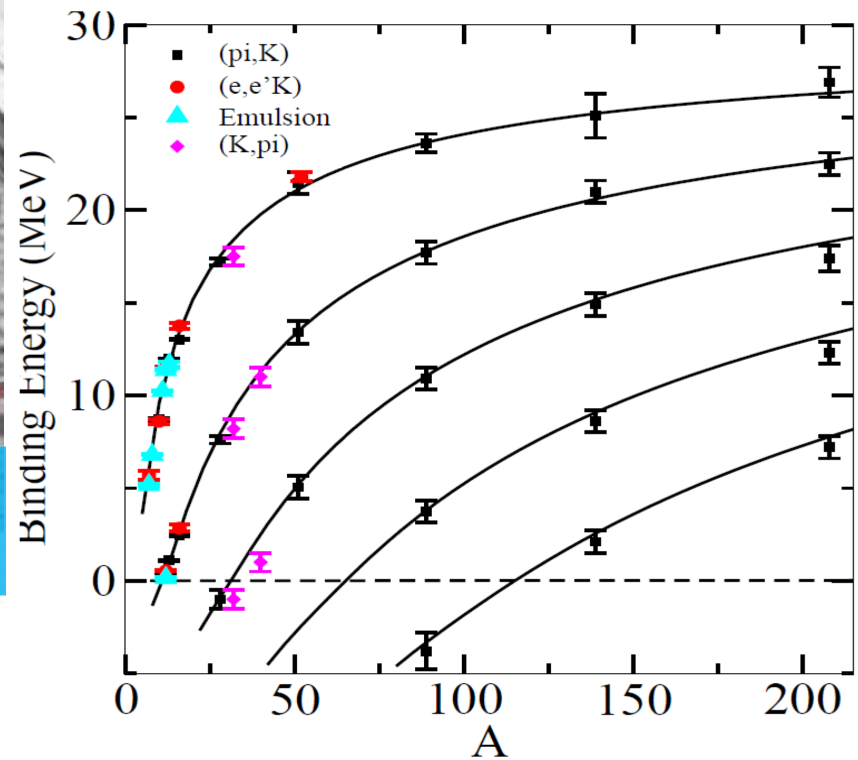
Hadron Hall


K1.8BR
K1.1BR/K1.1
K-pp systems, K atoms, $\Lambda(1405)$, η nucleus
COMET
K1.8
$\Lambda\Lambda$ and Ξ hypernuclei
Ξ atoms, YN scattering
H dibaryon
S= -2
KL
High-p
K1.1
γ-spectroscopy and weak decays of Λ hypernuclei
Σ nuclear systems
YN scattering
ϕ nucleus bound states
Hadron mass in nuclei
Nucleon structure (Drell-Yan)
Charmed baryons
et
S= -1
systems
HR
K10
p
Single particle energies of Λ
n-rich Λ hypernuclei
Magnetic moments of Λ hypernuclei
Weak decays of Λ hypernuclei
Ξ^*, Ω^* spectroscopy
$\Lambda\Sigma$, $\Sigma\Sigma$, $\Lambda\Xi$, $\Sigma\Xi$ interactions
Ω hypernuclei
Multi K mesons in nuclei
Charmonium Spectroscopy
Charmonium and D mesons in nuclei
Precise S= -1 exp.

HR Line for Λ single particle energies



Intensity: ~9x10^{8} pion/pulse
(1.2 GeV/c, 56 m, 1msr*%,
270kW, 6s spill, Ni 54mm)
Δp/p~1/10000



plot by Millener

Precise measurement of s.p.e. of Λ

- (e,e'K$^+$) at Jlab (heavier hypernuclei)

  Absolute accuracy ~100 keV

  Resolution ~400 keV

- (π+,K+) (and (π-,K+)) at HR line

  Absolute energy (syst. err.) calibrated by (e,eK+) ~100 keV

  Resolution ~200 keV(?)

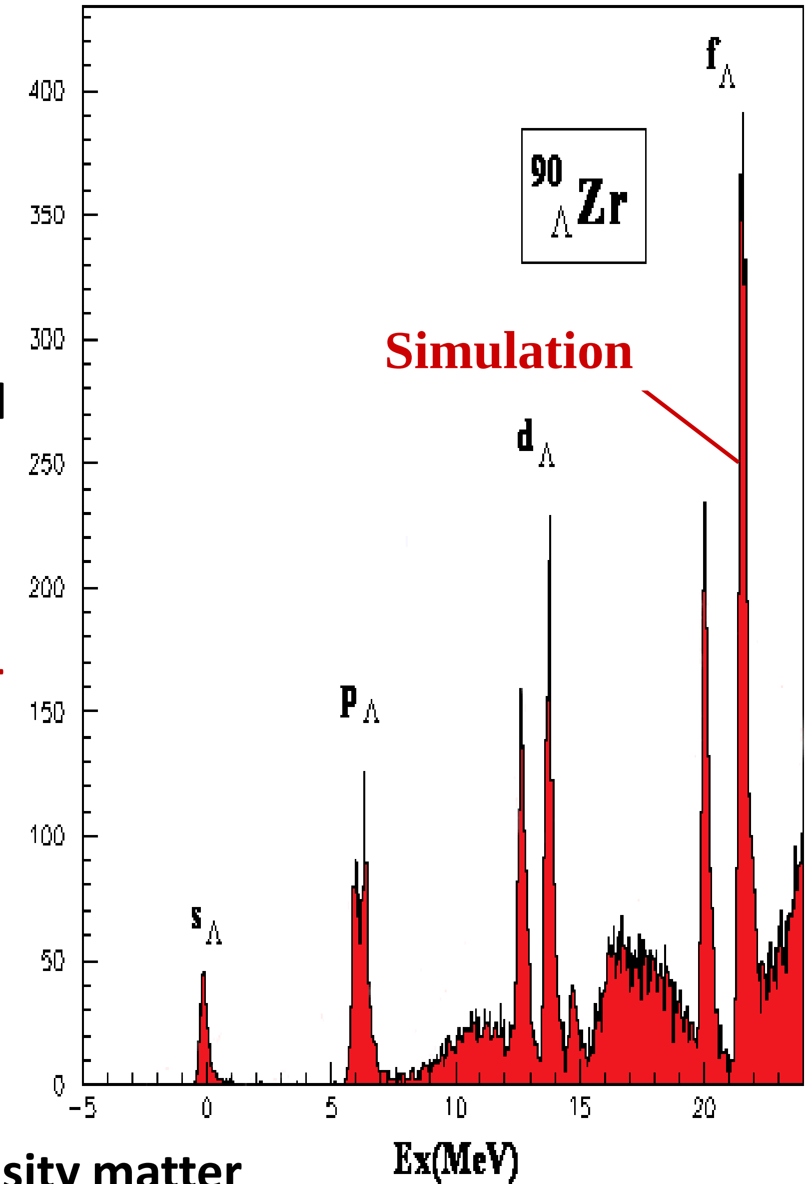
- γ spectroscopy for E1($p_\Lambda \rightarrow s_\Lambda$) at K1.1

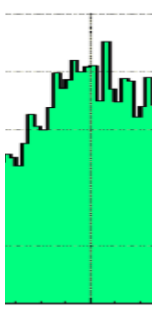
  Accuracy of energy spacing

  a few keV (FWHM)

E(s_Λ, p_Λ, d_Λ, f_Λ,..) < 100 keV accuracy

E(s_Λ) – E(p_Λ) < a few keV accuracy





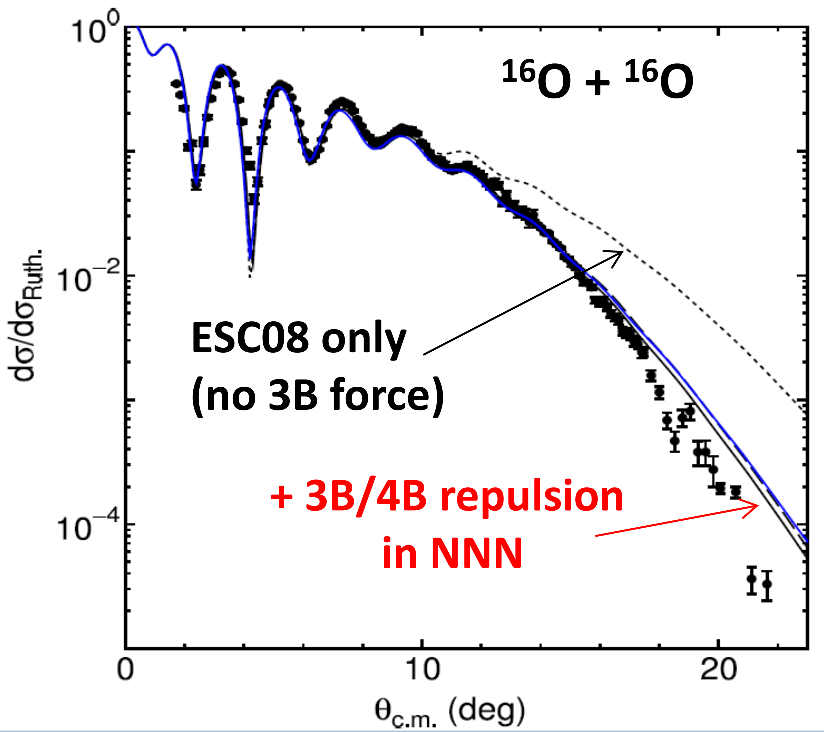
Density dependence of YN interaction (YNN int.) -> Understanding of high density matter

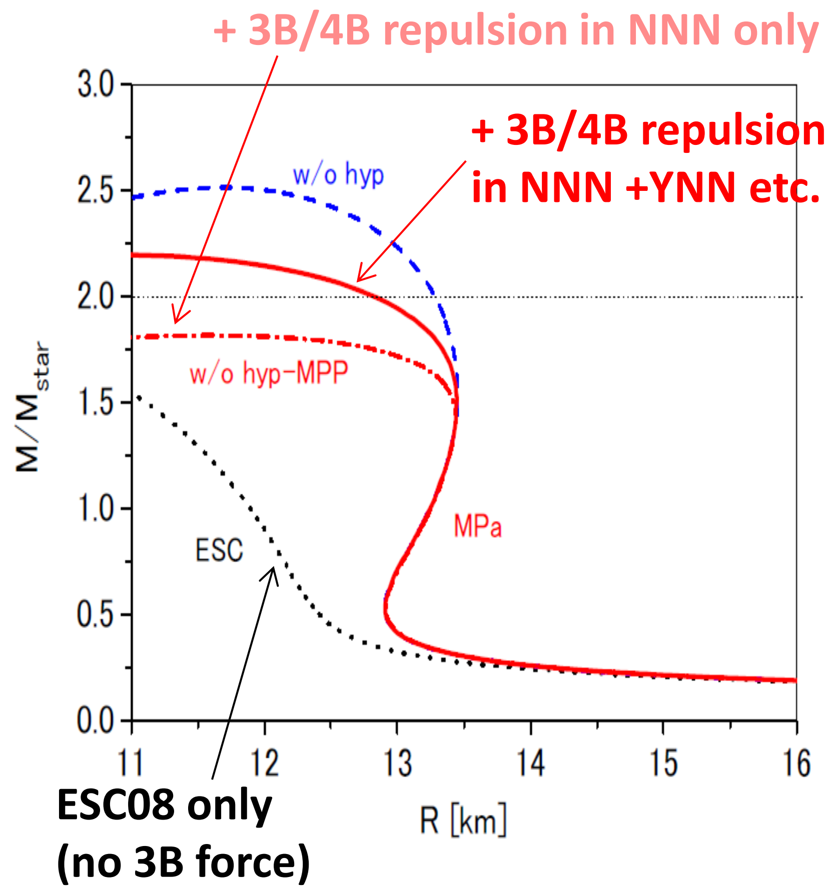
NS mass and universal 3B repulsion

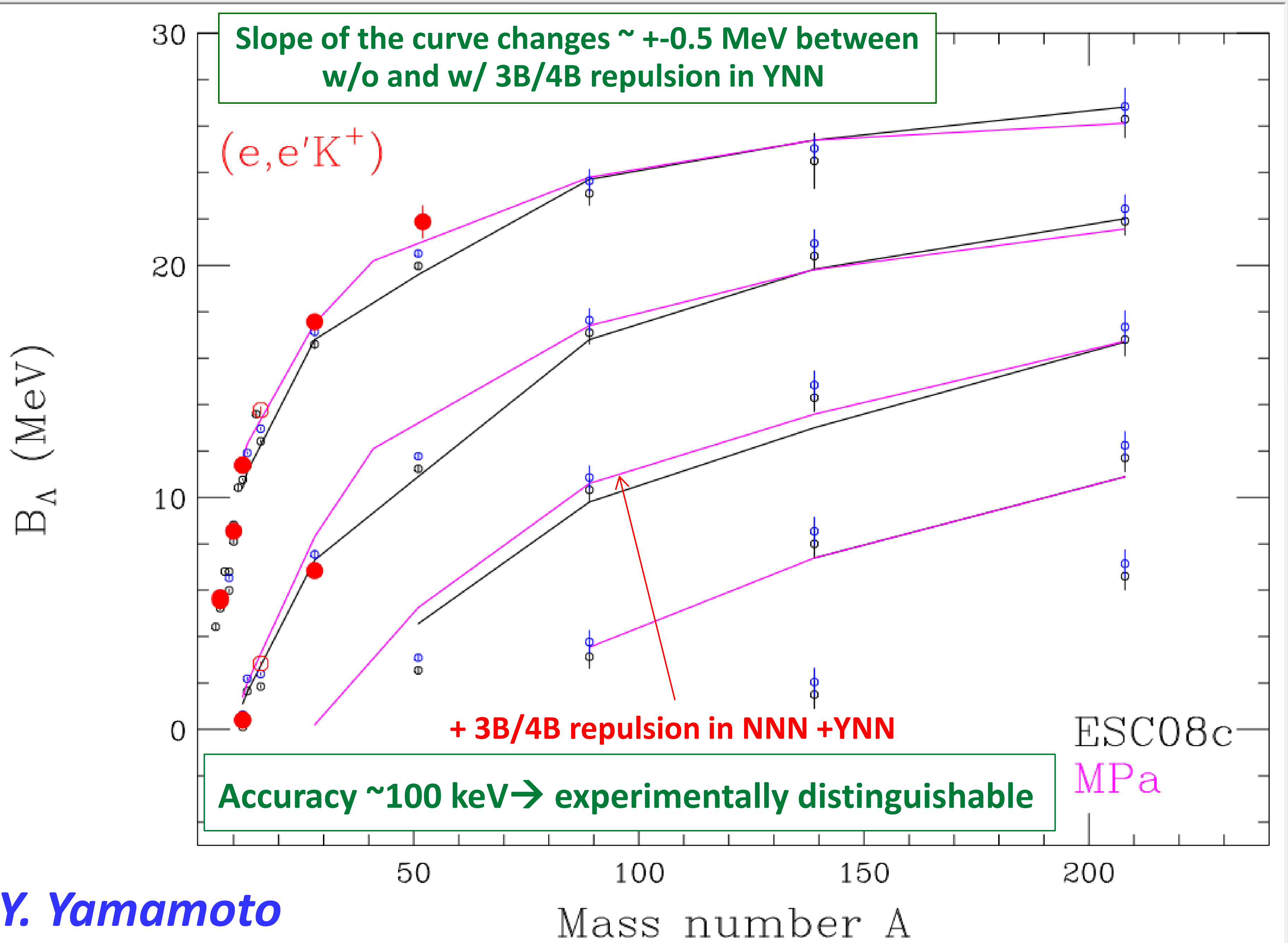
Nijmegen ESC08 interaction model reproduces (almost) all the hypernuclear and NN/YN scattering data well.

Add "3body/4body repulsion in YNN, YYN, YYY" with the same size as the NNN/NNNN repulsion which reproduces HI collision data ("universal 3B repulsion").

Y. Yamamoto, Th. Rijken et al.
Phys.Rev. C88 (2013) 2, 022801
arXiv:1406.4332 [nucl-th]



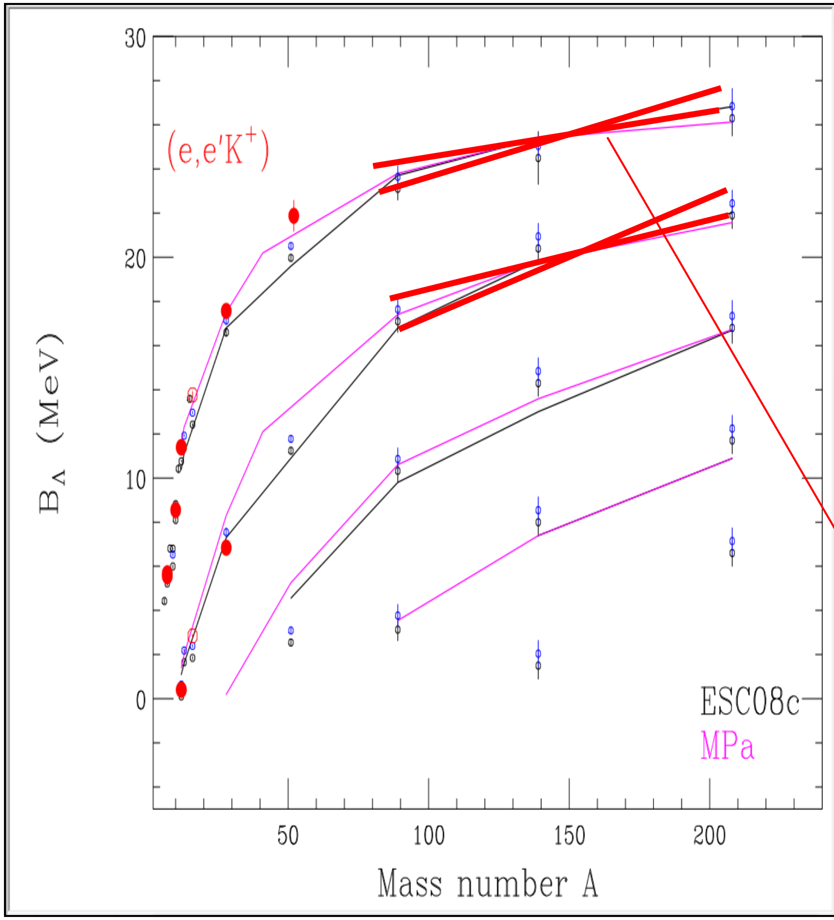


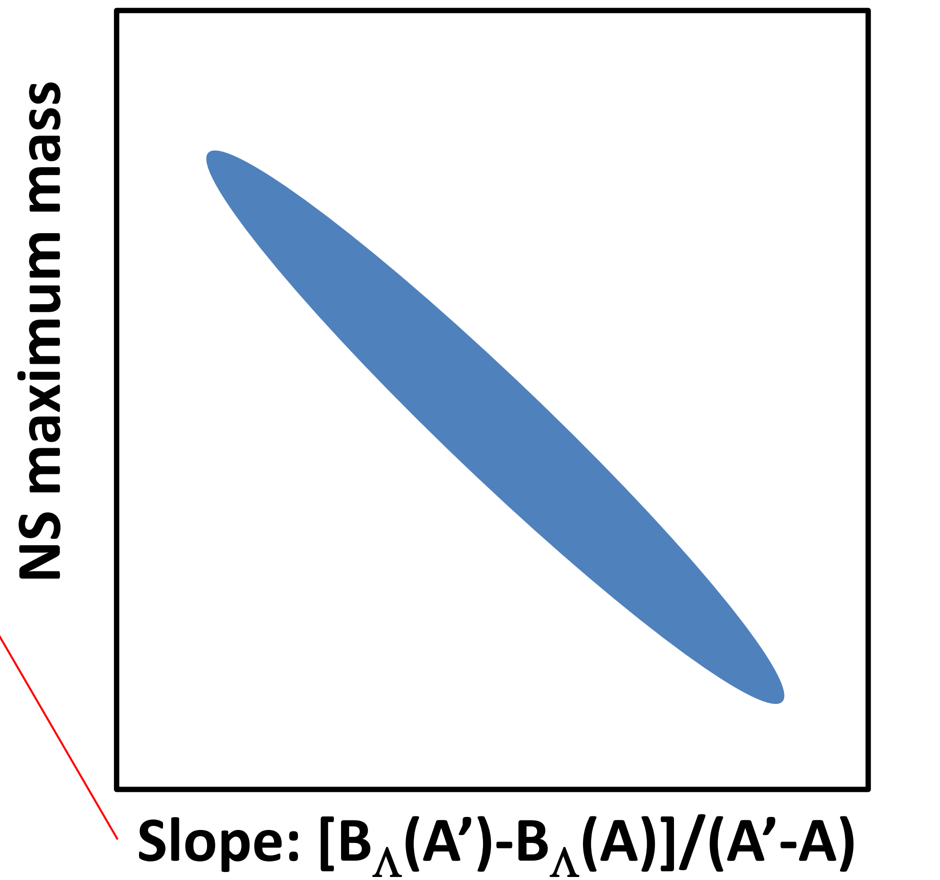


Slope of the curve changes ~ +-0.5 MeV between
w/o and w/ 3B/4B repulsion in YNN
(e,e'K+)
30
20
10
0
B_Λ (MeV)
50
100
150
200
Mass number A
+ 3B/4B repulsion in NNN +YNN
ESC08c
MPa
Accuracy ~100 keV→ experimentally distinguishable

Y. Yamamoto

Is there a correlation between the slope in $B_\Lambda(A)$ plot and the NS maximum mass Independently of theoretical treatment ??





I ask theorists to examine whether such correlation exists or not.

6. Summary

- J-PARC experiments provide BB forces and baryon properties and behavior in-medium, giving clues to understand neutron star matter.
- Neutron-rich hypernuclei are being studied via (π^-,K^+) to investigate ΛNN force in n-rich environment. ${}^{6}_{\Lambda}H$ was not observed.
- γ-spectroscopy of Λ hypernuclei will start soon. ${}^{4}_{\Lambda}He$ and ${}^{19}_{\Lambda}F$ will be investigated first.
- To study the strongly repulsive potential, $\Sigma^{\pm}$-p scattering experiment is being prepared.
- The emulsion experiment for S=-2 systems will start from 2016 for more $\Lambda\Lambda$ hypernuclear events and Ξ atomic X-rays. Ξ hypernuclear spectroscopy will follow it.
- Extension of J-PARC Hadron Hall is planned. One of new experiments is precise (π,K^+) spectroscopy for Λ single particle energies, which may give a clue to solve the hyperon puzzle in neutron stars.

Λ hypernuclear spectroscopy is now a precision science.